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INTERSTATE AIR POLLUTION STUDY, PHASE II PROJECT REPORT. VI. EFFECTS OF AIR POLLUTION

J. D. Williams, et al

National Center for Air Pollution Control
Cincinnati, Ohio

December 1966

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INTERSTATE AIR POLLUTION STUDY

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PHASE II PROJECT REPORT

VI. EFFECTS OF AIR POLLUTION

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INTERSTATE AIR POLLUTION STUDY

PHASE II PROJECT REPORT

VI. EFFECTS OF AIR POLLUTION

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Details of illustrations in
this document may be better
studied on microfiche.

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE

Public Health Service

Bureau of Disease Prevention and Environmental Control
National Center for Air Pollution Control
Cincinnati, Ohio

December 1966

FOREWORD

The Interstate Air Pollution Study was divided into two phases. Phase I, a general study of the overall air pollution problems in the St. Louis - East St. Louis metropolitan area, was conducted to determine specific activities that would require further study in Phase II of the project. The effort was divided into two phases to provide a logical stopping point in the event that interest and resources for proceeding further might not materialize. The necessary impetus did continue, however, and the Phase II operation was also completed.

The Phase I operation resulted in a detailed report, designed primarily for use of the Executive Committee members and their agencies in making decisions concerning the Phase II project operation. A Phase I summary report was also prepared; it received wide distribution.

Numerous papers, brochures, and reports were prepared during Phase II operations, as were some 19 Memorandums of Information and Instruction concerning the project. All of these documents were drawn upon in the preparation of the Phase II project report. The Phase II project report consists of eight separate volumes under the following titles:

I. Introduction
II. Air Pollutant Emission Inventory
III. Air Quality Measurements
IV. Odors - Results of Surveys
V. Meteorology and Topography
VI. Effects of Air Pollution
VII. Opinion Surveys and Air Quality Statistical Relationships
VIII. Proposal for an Air Resource Management Program.

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VI. EFFECTS OF AIR POLLUTION

INTRODUCTION

The Air Quality Goals Subcommittee, appointed under provisions of item 5-A-5 of the Interstate Air Pollution Study Phase II Project Agreement, reviewed literature, met with consultants in the air pollution effects field, and selected air quality goals for consideration by the Project Executive Committee. The Committee limited its consideration to goals because it does not have authority to adopt air quality standards, a function restricted to legally constituted governmental agencies. The Committee does, however, by approving this report, accept the consensus of professional and technical personnel. The explanations of effects levels presented herein were prepared by the staff of the Public Health Service Technical Assistance Branch who utilized the advisory resources available within the Division of Air Pollution.

The effects of air pollution, as a program element, is only one part of an air resource management program; the relationships among the several elements are shown in the diagram in Figure 1. Air pollution effects, air-quality levels, and pollutant emissions are the major program elements that provide the basis for air quality goals. Actually, if no consideration were given to the length of time needed to reach goals or to the priorities of community needs, air pollution effects would be the only program element to be considered in establishing goals. The suggested goals listed in Table 1, however, are based on the air quality (indicating major

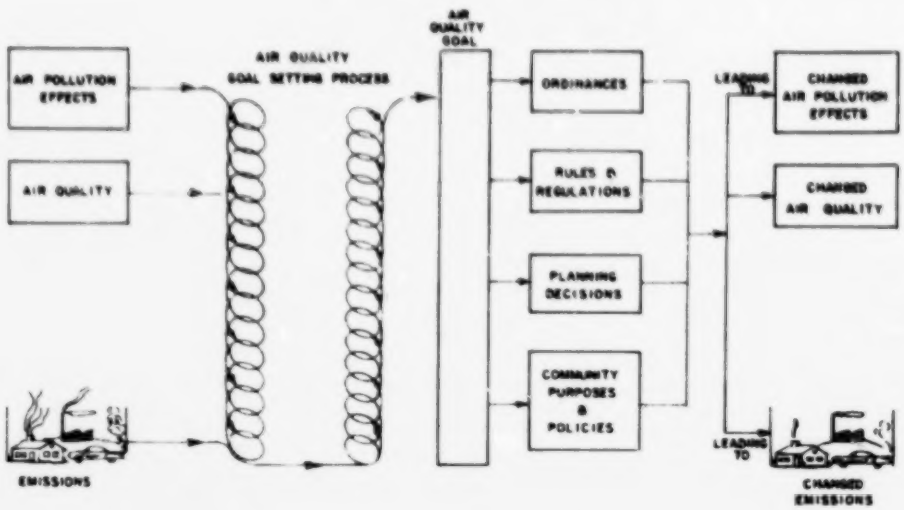

Figure 1. Air resource management flow diagram.

Table 1. SUGGESTED AIR QUALITY GOALS FOR INTERSTATE AIR POLLUTION STUDY AREA[a]

Sulfur oxides

Sulfation, measured by lead peroxide candle method

Maximum annual average 0.25 mg SO_3 per 100 cm^2 per day
Maximum month 0.5 mg SO_3 per 100 cm^2 per day

Sulfur dioxide, measured by West-Gaeke or conductometric methods

Maximum annual average 0.02 ppm
24-hr average 0.1 ppm not to be exceeded over 1 percent of the days in any 3-mo period
1-hr period not to exceed 0.20 ppm more than once in any 4 consecutive days
5-min period not to exceed 0.50 ppm more than once in any 8 hr

Suspended sulfate, measured by high-volume sampler

Maximum annual average not to exceed 4 µg per m^3
Not to exceed 12 µg per m^3 over 1 percent of time

Sulfuric acid

Maximum annual average not to exceed 4 µg per m^3
Not to exceed 12 µg per m^3 over 1 percent of time
Not to exceed 30 µg per m^3 hourly average over 1 percent of time

Hydrogen sulfide, measured by AISI spot sampler using lead acetate impregnated paper

0.05 ppm 1/2-hr average not to be exceeded over 2 times per yr
0.03 ppm 1/2-hr average not to be exceeded over 2 times in any 5-consecutive-day period

Oxidant (total), measured by potassium iodide colorimetric method

0.15 ppm for 1 hr (not to be exceeded)

Carbon monoxide, measured by nondispersive infrared method of measurement

30 ppm for 8 hr
120 ppm for 1 hr

Dustfall, measured by settled particulate accumulated in dry jars for 1 mo

10 tons per mi^2 per mo, 3-mo average above background in all areas except those zoned heavy industrial
(Use 5 tons per mi^2 per mo background)
25 tons per mi^2 per mo, 3-mo average above background in zoned heavy industrial areas
(Use 5 tons per mi^2 per mo background)

Suspended particulate, measured by high-volume sampler

75 µg per m^3, annual geometric mean
200 µg per m^3, annual 99th percentile

Soiling index, measured by AISI spot sampler

0.4 Coh per 1,000 lineal ft, annual geometric mean

---

[a] Abbreviations defined

mg	= milligram	µg	= microgram
cm	= centimeters	m	= meter
ppm	= parts per million	mi	= mile
hr	= hour	ft	= feet
mo	= month	Coh	= function of optical density - see reference 1

Note: All goals, unless otherwise stated, apply to any place where people live or an undesirable effect could result from levels above the goal.

types and amounts of pollutants present) as well as actual and anticipated effects of air pollutants in the Interstate Air Pollution Study area. They do not provide a great factor of safety in health matters, nor do they include the time that might be needed to reach those goals without undue disruption of normal community life. Timing should be specified, however, in provisions of suggested ordinances that will implement the air-use plans.

The effects of air pollution, have been considered in this report from the viewpoint of a consultant whose task has been the development of a set of goals that will meet the future needs of the area. Some of the quantitative relationships between effects and air quality levels have not yet been established, but enough is known that a guide for a constructive air resource management program has been provided for the Interstate Air Pollution Study area. This guide (Table 1) is intended to serve the needs of the Study area only, and is not intended to have general application.

The frame of reference in which this report has been prepared recognizes that approaches of the past are not always valid in the present. For example, in the field of public health, past successes have stemmed from the control of epidemics. These successes have been based on single-cause, single-effect relationships. Few, if any, of these simple or direct relationships seem to exist in the complexities of community air pollution problems. A departure of public health programs from the orientation of epidemic control has been recognized for those modern programs in health that are being oriented toward a relatively new priority need, the control of chronic diseases and the conditions causing them. In the air pollution field comparable situations are represented by multiple types, combinations, and levels of air pollutants, which, combined with other stresses on individuals or groups, cause undesirable effects. Program needs in both instances only remotely resemble the old priority need established for control of epidemics. This report's frame of reference also recognizes that community capability has changed and that this increased capability holds the promise of effective action toward improving air quality. An example of the importance of increased community capability is apparent from a quick review of the air pollution problems in London, England, and other manufacturing centers. As long ago as 1907, deaths associated with sulfur dioxide were reported,[2] but little if any action was taken to alleviate this admittedly undesirable situation until community competence in many activity areas had advanced and met the established priority needs of these cities and their citizens.

The frame of reference recognizes that metropolitan areas have decided to develop their central city areas for new purposes. By way of example, the old purpose might very well be compared with an extractive operation such as mining or lumbering. The new metropolitan central city area's purpose contrasted with the old, emphasizes people rather than production or even sales. In effect, these metropolitan areas have, without consideration of air pollution and probably many other important factors, committed themselves to a mixed and varied land use, at least in their central areas. Major decisions left for the future pertain to how these many mixed and varied land uses can be made to function in a compatible manner.

Recognition has been given to the competition between major metropolitan areas for people, money, and talent; in effect, viability of the total metropolitan area as contrasted with competition among the area's several parts, as has often been the case in the past.

Last, but not least, recognition has been given to the beginnings of attempts to come to grips with the urban environment. Those attempts are directed toward shaping the urban environment so that it develops the best in its citizens, while making living in this urban environment worthwhile, and imparting beauty and a sense of well being to not only those people who live there, but also to those who visit. For example, Oscar Sutermeister,[3] in a paper presented at the annual conference of the American Institute of Planners in 1961, said: "The planner may ask the health officer to consider such questions as 'Does mixture of land uses along an arterial road bounding a residential neighborhood promote well being? Does the existing level of traffic noise promote well being?' " To these it would be easy to add many more, such as: Does the existing quality of air in our cities promote well being? Do community decisions made now adequately consider future air quality?

In the preparation of this report the following guidelines selected by the Subcommittee on Air Quality Goals have been used:

1. The quality of the air should not adversely affect the health of even the most sensitive or susceptible groups in the population.

2. Pollutants should not be allowed to reach concentrations that would cause a nuisance, such as the sensation of unpleasant tastes or odors.

3. Pollutant concentrations should not reach levels that would be damaging to animals, ornamental plants, or agricultural crops.

4. Pollutants should not reach concentrations that would significantly reduce visibility, especially visibility reductions that would, or could, be a hazard to transportation.

5. Soiling, corrosion, and damage to materials, as well as adverse economic effects, should not occur to any great extent. (These effects have been considered in a way that points toward the economic savings that could result from improvement in air quality.)

A few words indicating the differences among standards, goals, and criteria are in order. Goals relate to objectives that are not necessarily legal standards, nor need they be linked to obvious health effects or vegetation damage. They should relate to what is best for the total development of the human resources of the community. This does not mean complete freedom from air pollution, or no stress on the citizens, but does dictate an approach directed toward what is best for the citizens' total development. Standards, by contrast, are specified by law. They may be as broad in their meaning as goals, or they may be limited to some effect such as health or vegetation damage. Criteria refer to relationships between air quality and various effects of pollution, word meanings equated with numerical values.

Methods Available for Setting Air Quality Goals

Many methods have been used in the developing air pollution field for establishing air quality goals for particular kinds of pollutants. Much of this work has been based on knowledge of the effects of single pollutants, often under conditions and with populations that are not typical of those exposed to air pollution. Unfortunately, little is known of the synergistic effects of combinations of pollutants, although

it is known that such effects exist. Generally, in goal setting relating to the effects of air pollutants on health, as knowledge became more detailed from research and experience, the standards of maximum permissible human exposure have had to be progressively lowered. The acute effects on human beings have been much easier to evaluate than the chronic effects, particularly those chronic effects that may evolve after a great many years of exposure to low levels of air pollution. Long-term effects are extremely hard to evaluate, and not much effort has been put forth for their definition since the least productive part of the population is most affected. Most of the people suffering from long-term exposure have already lived the major part of their lives and carried out their reproductive function to sustain society. The effects of air pollution on them, therefore, arouses less attention than similar effects upon young and vigorous persons.

The Russian philosophy in establishing maximum permissible exposures to air contaminants is perhaps the most rigorous currently proposed.[4] It takes the position that any detectable effect upon the human organism that can be measured by any known method in an average group of exposed individuals should establish the maximum allowable standard. These levels are frequently far below that which the individual can recognize by sensory perception, and they may or may not have long-range or chronic effects on the individual. The methods include testing exposed individuals for such hidden effects as changes in optical chronaxy in the eye, changes in brain waves, threshold odor, and any other measurable effects for which there are test procedures. The standard is set by the most sensitive measurement that first shows the effect of exposure to an air pollutant. At the other end of the philosophy spectrum, some persons advocate that standards should be established only upon the basis of proved damage to the human organism.

A reasonable approach to the establishing of air quality goals would apparently demand that such goals be sufficiently low so that no adverse health effect or impairment of bodily function would occur, even in the most susceptible or sensitive group in the population. As an example, goals would not be based on currently established threshold limit values applicable to the active male working population exposed for 8 hours a day. Instead, they would be based on the older part of the population suffering from chronic health problems that would predispose them to the effects of acute air pollution episodes to which such people have been shown to succumb in the past.

In summation, air quality goals for those contaminants that affect health should be based upon concentrations at which sensitive groups of individuals in the population would not be affected. This would not, however, preclude all effects upon all hypersensitive individuals.

Where health effects are not believed to exist, other criteria must be used to set goals. Where sensory effects to humans are involved, it would appear that the public would wish that the standards would not allow the sensory threshold to be exceeded as related to irritation, taste, or odor, at least in the residential and general-public-use types of environment. When economic effects serve as the basis for goals, the public would probably wish that resulting standards would not allow demonstrable damage to animals or to ornamental plants or crops, and that corrosion and other damage not appreciably shorten the usable life of building materials, instruments, and fabrics. Obscuration of vision should not be so severe that transportation is affected or rendered more hazardous. Where nuisance

effects are the primary concern, it would seem that the public would readily accept standards that would prevent the filth in the environment from being objectionable to most individuals.

Aesthetic values such as the beauty of an unobscured view are difficult to assess, but may be important under certain circumstances. Certainly the Los Angeles and Denver areas have lost much of their natural beauty from smog obscuring the mountain ranges around them. Certainly St. Louis will lose much in addition to economic costs if visitors to the Arch and the residents of the fashionable high-rise apartments frequently look out upon a sea of air pollution instead of the suburbs to the west and the bottom land and bluffs to the east.

SULFUROUS COMPOUNDS

The effects of sulfurous compounds are summarized in Table 2. The sulfurous compounds in the atmosphere are primarily from the sulfur oxides group, which consists of sulfur dioxide, sulfuric acid, and sulfate salts. Hydrogen sulfide, mercaptans, and other such compounds occur occasionally, but generally in small amounts or in limited parts of urban atmospheres. The effects of sulfurous compounds reported herein are related to pollutant concentration and to exposure time. Although expressed in terms of sulfur dioxide, concentrations are reported with the assumption that normally occurring amounts of sulfuric acid and suspended particulates are also present.

Sulfur Oxides

The suggested goals for sulfur oxides (determined by measuring sulfur dioxide) in the Study area are dual. On the basis of observed effects, an annual arithmetic mean concentration not to exceed 0.02 part per million is recommended. In addition to this annual goal, the sulfur dioxide concentrations should not exceed 0.1 part per million more than 1 percent of the time in any 3-month period. Both of these goals are to relate to 24-hour sulfur dioxide measurements based on the West-Gaeke or equivalent method of analysis. These concentrations are not to be exceeded in any place where people live, or where an undesirable effect may occur.

The sulfur oxides group is one of the most prevalent man-made pollutants in the United States and is concentrated in major metropolitan areas. This widespread condition results from the abundant use of fossil fuels, such as coal and oil, used for power and heat. (See report Volumes II - Air Pollutant Emission Inventory and III - Air Quality Measurements.)

The effects of sulfur oxides reported in Table 2, with the exception of those in the "brief exposure" section, do not ordinarily derive solely from the presence of any one sulfur oxide or, necessarily, the sulfur oxides as a group. They are for the most part observed effects associated with sulfur oxides when various concentrations of these pollutants and other pollutants (the normal situation), have been present in urban atmospheres. Because of the interreactions among pollutants and the reactions of pollutants with oxygen and water in the atmosphere, as well as the influence of sunlight and temperature on these reactions, the effects of sulfur oxides pollution in a total atmosphere may be quite different from the effects of sulfur oxides under laboratory conditions. The effects reported, therefore, are not primarily expressions of cause and effect that can be duplicated pre-

Table 2. SUMMARY OF EFFECTS OF SULFUROUS COMPOUNDS

Sulfur dioxide concentration, ppm	Exposure period and effect	Measurement method[b]	Reference
	Yearly exposure		
Trace	Metal corrosion begins[a]	PbO_2	5
0.01 to 0.02	Significant metal corrosion[a]	PbO_2	5
	Impaired pulmonary function[a]	PbO_2, W.G.	6,7
	Increased cardiovascular morbidity[a]	PbO_2, W.G.	6,7
0.02 max annual avg	Air-quality goal for Study area		
0.02 to 0.03	Increased respiratory death rates for area studied[a]	PbO_2	8
	Detectable chronic injury to perennial vegetation[a]	T.A.	9
	2- to 4-day exposure		
0.07 to 0.25	Hospital admissions for cardio-respiratory diseases increase[a]	H_2O_2	10
0.20 to 0.30 for 3 days	Rhinitis, sore throat, cough, and eye-irritation rates increased[a]	E	11,12
	Mild to acute sensitive vegetation injury	P.G.	13
0.20 to 0.86 for 3 days	Cardio-respiratory mortality increased[a]	H_2O_2	14
	Acute vegetation injury	P.G.	13,15
	24-hr exposure		
0.21	Bronchitic patients' health deteriorates[a]	H_2O_2	16
0.1 not to be exceeded over 1% of time in any 3-mo period	Air-quality goal for Study area		
0.25	Increased total death rates[a]	H_2O_2	16
0.28	Detectable injury to sensitive vegetation	P.G.	13
	Brief exposures		
0.04	Visibility reduced to 10 mi at 70% relative humidity	C	
0.08	Cortical conditioned reflexes produced. Repeated 10-sec exposures	NMI	17
0.10	Visibility reduced to 4 mi at 70% humidity	C	
0.20 for 1 hr not to be exceeded over once in any 4 consecutive days	Air quality goal for Study area		
0.30	Taste threshold	P.G.	18
0.50	Visibility reduced to 0.85 mi at 70% humidity	C	
0.50 for 5 min not to be exceeded over once in any 8-hr period	Air-quality goal for Study area		
0.5 for 1 sec	Odor threshold	P.G.	19
0.5 for 4 hr	Detectable injury to sensitive vegetation	P.G.	13
0.5 for 7 hr	Acute injury to trees and shrubs	P.G.	15
1.0 for 10 min	Respiration and pulse rates increase	P.G.	20
1.6 for 1 to 5 min	Threshold for inducing measurable broncho-constriction in healthy people	P.G.	21

[a] Effect determined for ambient air-quality conditions. Other effects are calculated or determined by laboratory experiment.

[b] PbO_2 - lead peroxide candle method
T.A. - by Thomas autometer
E - by electroconductivity
C - calculated effect
W.G. - West-Gaeke method
H_2O_2 - hydrogen peroxide method
P.G. - pure gas used
NMI - no method indicated

cisely from one location to another, but rather they are useful values derived from what has actually been taking place in urban atmospheres.

Each of the sulfur oxide compounds - sulfur dioxide, sulfuric acid, and sulfate salts - contributes individually to the effects of sulfurous pollution. The proportions of the compounds, of course, vary in a complex manner over any geographical area, both in regard to the proportions of the compounds and the time or times during which they occur. Over a long period, it is expected that the proportions of the compounds would remain roughly the same from place to place and season to season. Studies involving volumetric and sulfation measurement methods during two winter seasons in the St. Louis area tend to confirm this expectation.

Since the methods of measuring the sulfur dioxide component have been more fully developed than methods of measuring other pollutants, and since most investigations reported from other places have relied heavily on measurements of sulfur dioxide, concentrations of this gas have been used to express the concentrations of sulfur oxides. Considering that the sulfur dioxide measurements are an index of effects, the higher-than-normal sulfation levels in the Study area may be found at some time to have some major significance, such as indicating the presence of significant levels of sulfuric acid.

In the documented air pollution disasters in Belgium (1930),[22] Donora, Pennsylvania (1948),[23] New York City (1953 and 1963),[12] and London (1952 and 1962),[24,25] large numbers of people became ill, and many died. All of these episodes occurred in heavily industrialized areas during relatively brief periods of weather conditions that prevented dispersal of air pollutants. Sulfur dioxide concentrations were abnormally high, as were the concentrations of other gaseous and particulate pollutants. Although the pattern of effects was not uniform in all these episodes, generally speaking, the elderly, the very young, and those with preexisting cardiorespiratory disease were affected most.

The evidence is considerable that sulfur oxides pollution aggravates existing respiratory disease in humans and contributes to its development. Sulfur dioxide gas alone irritates the upper respiratory tract. Adsorbed on particulate matter, the gas can be carried deep into the respiratory system to injure lung tissue. Sulfuric acid in a certain particle size, when inhaled, penetrates deeply into the lung to damage tissue.

Epidemiological, as well as clinical, study substantiates the evidence that certain portions of the population are more sensitive than others to sulfur oxides pollution. For example, prolonged exposure to relatively low concentrations of sulfur dioxide has been associated with increased cardiovascular morbidity in older persons. Prolonged exposure to higher concentrations of sulfur dioxide has been associated with an increase in respiratory disease death rates and an increase in complaints by school children of such symptoms as nonproductive cough, mucous membrane irritation, and mucous secretion. Furthermore, the residual air in the lungs of emphysema patients has been significantly reduced when the patients breathed outdoor air that had been filtered of its pollutants. Alveolar elasticity is apparently restored somewhat, or airway resistance is decreased by the cleaner air. The most important single factor in improving the feeling of well-being in chronic bronchitis patients has been decreases in the amounts of smoke and sulfur dioxide pollution.

Sulfur oxides pollution can also adversely affect the most robust persons of the population. Experiments in which human volunteers were exposed to sulfur dioxide concentrations several times higher than the 0.3-ppm taste threshold indicate that such exposure will produce pulmonary function changes, including increased respiration rates, decreased respiratory flow rates, and increased airway resistance. The impairment of function is greater when the sulfur dioxide gas is administered along with particulate matter.[26 27] The latter appears to increase the penetration of sulfur dioxide into the lung. Sulfur dioxide and particulates would be a normal combination found in urban atmospheres.

In other experiments involving sulfur dioxide concentrations below the taste threshold, cortical conditioned reflexes were produced. Tests made with concentrations at the taste threshold desynchronized the predominant wave in electroencephalograms and increased the sensitivity of the dark-adapted eye.

Dohan[28] studied the incidence of respiratory illness lasting more than 7 days in female employees in five cities. Results of this study showed a very high correlation (0.964) of the average concentration of suspended sulfate in the air in these cities with the rate of respiratory illnesses. The average sulfate concentrations for the cities ranged from 5 to 20 micrograms per cubic meter. During the non-influenza-epidemic years, the incidence of respiratory disease was more than twice as great in the city with the highest sulfate concentration than it was in the city with the lowest sulfate concentration. As one would expect, the incidence of total respiratory disease during the Asian flu epidemic of 1957-1958 was greater than in the same cities during nonepidemic years. In the city with the lowest concentration of suspended sulfates, the incidence of respiratory illness increased about 20 percent during the epidemic year, whereas in the city with the highest concentration of suspended sulfate, the incidence of respiratory illness increased approximately 200 percent. This was 10 times as great an increase in the city with the highest sulfate concentration as in the city with the lowest sulfate concentration. In absolute terms rather than percent increase, during the influenza year the incidence of respiratory diseases in the city with the highest sulfate pollution was more than five times as high as that in the city with the lowest sulfate pollution. There is, of course, the possibility that the sulfate concentrations measured indicate the presence of other pollutants that increase simultaneously with sulfate concentrations and that are contributory to adverse health effects or are even more damaging to health than the sulfurous compounds producing the sulfate.

Sulfuric acid mists and sulfates in the atmosphere scatter light and thus reduce visibility. Because sulfuric acid and sulfate are hygroscopic, they tend to cause fogs. These fogs decrease the amount of solar energy reaching the ground and, therefore, tend to stabilize the atmosphere so that pollutants are held in the affected area.

Prolonged exposure of all but the most resistant metals to any quantity of sulfuric acid accelerates corrosion. The corrosion rate increases rapidly as the pollution level rises. The effects of sulfur oxides on nylon and cotton fabrics have been studied to some extent during the Interstate Air Pollution Study. In fact, these studies have been some of the first of this type ever made. (See Materials Deterioration in the Study Area section of this report.) The effects of sulfur oxides corrosion on stone statuary and buildings has been recognized throughout the world. Damage to art objects, paper, leather, textiles, and paint is also a widespread problem.

Vegetation is acutely damaged by a few hours of exposure to concentrations of sulfur dioxide in excess of 0.25 ppm, and injury may be detected in many areas that have yearly average concentrations of 0.02 to 0.03 ppm. Vegetation sensitive to sulfur oxides disappeared many years ago in several parts of the Study area. Decreases in measured sulfur dioxide concentrations during the past 20 years, however, have allowed some species to reappear in the central part of the Study area (see Vegetation Damage section of this report).

Table 3 reports effects caused by different amounts of sulfuric acid (criteria). For the most part these criteria are derived from laboratory investigations and do not, like sulfur dioxide criteria (Table 2), represent conditions found in urban atmospheres. This is undesirable, but is understandable because of the major difficulties encountered in the measurement of sulfuric acid in urban atmospheres.

It has been postulated that the presence of sulfuric acid aerosol can be shown by comparison of sulfation candle results and West-Gaeke results. Correlations of results from paired samplers located at the same sites can be expected to differ for the two methods from site to site and city to city because the West-Gaeke method is specific for sulfur dioxide and the nonspecific sulfation method shows the presence of all sulfurous compounds that react with lead dioxide to form lead sulfate. The relative importance of sulfuric acid aerosol at any site, therefore, may be determined by comparing the difference in the sulfation and sulfur dioxide levels with the differences found for other sites. Volume III - Air Quality Measurements reports in some detail on the high sulfation levels found in the Study area. These levels were five times higher than those found in Nashville, Tennessee, and in the same range as those found in London, England. Sulfuric acid aerosol may, therefore, be more important in the Study area than sulfur dioxide levels would indicate.

The following quotation from the book, Air Conservation,[29] reports the principal effects of sulfuric acid on man and animal:

> "Sulfuric acid must have been the principal cause of the air pollution disasters of the Meuse Valley, Donora, and London. It (sulfuric acid) produces on a molar basis from 4 to 20 times the physiological response in animals as sulfur dioxide does. The effect of sulfuric acid mist is greatly influenced by the size of the mist particles. Those of intermediate size (about 1 micron in mean diameter) appear to be most injurious."

Sulfuric acid mist causes spots on the surface of leaves exposed to falling droplets. Discrete spots appear only when the drops are large enough to settle upon the leaf and wet its surface. Such damage occurs most often during foggy weather, which is conducive to both coalescence of droplets and to leaf wetting. As one would expect, nonwaxy leaves are more susceptible to this type of damage.

Sulfuric acid mist promotes corrosion and materials deterioration. Especially damaging to certain cloth materials, such as nylon, sulfuric acid causes the formation of pinholes and weakens cloth as a whole. Particulate matter in the air, depending upon its characteristics, may detract from or enhance the acid-mist effect.

A goal of 0.004 milligram per cubic meter for a maximum annual average (4 $\mu g/m^3$) and 0.030 milligram per cubic meter (30 $\mu g/m^3$), not to be exceeded as an hourly average over 1 percent of the time, is suggested for the Interstate Air

Table 3. EFFECTS OF SULFURIC ACID

Concentration, mg/m^3	Condition	Effects	Reference
0.004	Maximum annual average	Air quality goal for Study area	
0.030	1-hr average - 1% of time	Air quality goal for Study area	
0.05		Visibility less than 10 mi at 70% relative humidity (calculated)	
0.1		Visibility less than 5 mi at 70% relative humidity (calculated)	
0.15	6 to 10 times per day for 10 sec, 0.18 ppm SO_2 present	Produced cortical conditioned reflexes in humans	17
0.35	1-μ-diameter, 10-min exposure	40% increased respiration rate; 15 to 20% decreased respiratory flow rate in humans	30, 31
0.6		Odor and irritation threshold for humans	32
1.0		Recommended Threshold Limit Value, American Conference of Governmental Industrial Hygienists	
5.0		Coughing and irritation in normal individuals	30
4-40	10-min duration; 10 Normal, 1-μ particles, 62% relative humidity	Coughing, some bronchoconstriction, rales	33
4-40	60-min duration; 10 Normal, 1-μ particles, 62% relative humidity	Coughing, some bronchoconstriction, rales	33
12-36	30- to 60-min duration; 4 Normal, 1.5-μ particles, 91% relative humidity	More irritant than mist at same concentration at lower relative humidity	33

Pollution Study area. These concentrations would not entirely eliminate materials deterioration, but would, based on current information, provide reasonable protection of the public health.

Hydrogen Sulfide

Hydrogen sulfide is easily identified by it's distinctive rotten egg odor. Its effects include gastrointestinal disturbances, damage to lead-base paints, and emotional stress caused by its odor. Table 4 shows that concentrations greater than 500 ppm cause death; lower concentrations cause respiratory irritation resulting in nausea, vomiting, discomfort, loss of sleep, shortness of breath, and headache. Concentrations of 10 to 100 ppm can cause eye effects including conjunctivitis and keratitis.

The odor threshold for sensitive individuals is about 0.01 ppm and ranges up to 0.10 ppm, depending upon individual olfactory sensitivity. At higher concentrations the odor becomes progressively stronger and more disagreeable; it reaches intolerable levels at about 30 ppm.

Damage to lead-based or pigmented paints and paints containing mercury-based fungicides can be caused by hydrogen sulfide. Discoloration occurs when the metallic oxides react with the hydrogen sulfide to form metallic sulfides. The occurrence of this type of damage depends considerably upon the presence of water, which hastens the reaction and allows it to occur with smaller amounts of hydrogen sulfide. When the paint surface is moistened, damage may occur with exposures of less than 1 hour and concentrations as low as 0.1 ppm. Figure 2, a photograph of a garage in the Study area, shows the type of damage caused by hydrogen sulfide.

Table 4. EFFECTS OF HYDROGEN SULFIDE FROM BRIEF EXPOSURES

Concentration, ppm	Effects	Reference
0.003	Tarnishing of silver and copper occurs slowly	34
0.001 to 0.10	Odor threshold depending upon olfactory sensitivity	35-37
0.03 for 1/2 hr not to be exceeded more than twice in any 5 days	Air quality goal for Study area	
0.05 for 1/2 hr not to be exceeded more than 2 times/yr	Air quality goal for Study area	
0.01 to 0.3 for 30 min	Paint blackening in presence of water mist	38
1.0 for 30 min	Paint blackening under dry conditions	
3 to 5	Offensive intense odor	4
4 to 30	Eye effects noted by most people	39 43
20	Industrial hygiene threshold limit value	
20 to 30	Strong odor, intolerable at about 30 ppm	
20 to 40 for 5 hr	Damage to sensitive vegetation	44
50 to 500	Respiratory irritant subacute poisoning	45, 46
>500	Systemic poisoning, death	47

Odors and tarnishing of metals are other specific effects found in the Study area. These effects are found within small areas and are intermittent in occurrence. The hydrogen sulfide upper limit goal of 0.05 ppm, 1/2-hour average, not to be reached or exceeded over two times a year at any place where people live or an effect may be objectionable, is suggested. This concentration would be detected as odors by some people, and some tarnishing of metals would occur; but if the goal is met, the frequency of such occurrences would be low.

CARBON MONOXIDE

Table 5 presents carbon monoxide criteria. The toxic action of carbon monoxide is related primarily to its affinity for hemoglobin, the oxygen-carrying component of blood. Human hemoglobin has an affinity that is about 200 times greater for carbon monoxide than it is for oxygen; therefore, a relatively small concentration of carbon monoxide in the inhaled air can tie up significant quantities of hemoglobin as carboxyhemoglobin. Hemoglobin is then unavailable for the transport of oxygen to the various body tissues. Secondary, though probably important, effects of carbon monoxide result from carboxyhemoglobin inhibiting the dissociation of oxygen and hemoglobin molecules. This further reduces the body's oxygen supply. Carbon monoxide in the blood also reduces the partial pressure of oxygen, as a gas, in the blood, and thereby lessens the moving force that causes the oxygen to diffuse into the tissues.

The amount of carbon monoxide within the body is related to both its concentration in the air and the length of time the individual is exposed. Unless the concentration in the air is sufficient to bring about death, an equilibrium condition is established between the carbon monoxide in the air breathed and that in the blood.

Figure 2. Example of paint damage caused by hydrogen sulfide in Study area.

Table 5. EFFECTS OF CARBON MONOXIDE[a]

Concentration, ppm	Exposure time	Effects	Reference
5	20 min	Reflex changes in the higher nerve centers	4
5 to 10	-	Average levels of CO in St. Louis and most large cities	48
30	8 hr or more	Impairment of visual and mental acuity (5% carboxyhemoglobin)	49-51
30	8 hr	Air quality goal for Study area	
45	-	Peak concentration at St. Louis CAMP Station	48
70 to 100	-	Maximum levels occurring in some large cities	49
120	1 hr	Air quality goal for Study area	
200	2 to 4 hr	Tightness across the forehead, possible slight headache	52
500	2 to 4 hr	Severe headache, weakness, nausea, dimness of vision, possibility of collapse	52
1,000	2 to 3 hr	Rapid pulse rate, coma with intermittent convulsions, and Cheyne-Stokes respiration	52
2,000	1 to 2 hr	Death	52

[a] All effect levels pertain to healthy individuals. Specific effect levels for individuals who for other reasons are approaching the levels of tolerability are not available.

In the concentration range of 0 to 100 ppm carbon monoxide, after sufficient time has elapsed to establish equilibrium, each 1 ppm of carbon monoxide has inactivated approximately 0.17 percent of the body's hemoglobin. The time necessary for equilibrium to be reached is a matter of hours, however, Both time and concentration must, therefore, be considered in determining effects.

Acute Effects

The oxygen deficiency that results from exposure to carbon monoxide is a reversible chemical asphyxia, a type of asphyxiation or oxygen deficiency. There is no satisfactory evidence to indicate that permanent ill effects occur from single acute carbon monoxide exposures that do not result in a loss of consciousness; however, when poisoning is severe enough to cause loss of consciousness, some damage to the brain, central nervous system, and circulatory system may occur. The degree of damage incurred is related to the length and severity of the asphyxia.[52]

Impairment of body function is detectable at carboxyhemoglobin levels as low as 5 percent in the blood. Such levels could result from exposure to 30 ppm carbon monoxide for an 8-hour period.[49-51] Effects caused by such exposure involving higher nerve centers include impairment of the ability to think and see clearly, a faculty very important to motor vehicle drivers. Detectable effects caused by

levels of 1.7 ppm for 24 hours affect the reflex actions in the higher nerve centers (such as light sensitivity of the eye, optical chronaxie, and the cerebral biocurrents).[4]

Sensitive Groups

For persons with certain types of preexisting physical disabilities or illnesses, the concentrations required to produce effects can be considerably less than those causing effects in healthy people. Included among this group would be persons with one or more of the following conditions: anemia, certain forms of heart disease, emphysema, a high metabolic rate (e.g., those with thyrotoxicosis or fever), and bronchial asthma.

In addition to those having an increased susceptibility because of certain disease conditions, there are others, who, because of where they are or what they have been doing, may exhibit an increased susceptibility. For example, those people at high altitude, in high temperature and high humidity, or persons with significant preexisting amounts of carboxyhemoglobin in their blood resulting from their occupation, from smoking (which has been found to produce carboxyhemoglobin levels of up to 8 percent),[53] or from traffic may be thought to be suffering from chronic effects of carbon monoxide when in fact they have accumulated acute levels of carboxyhemoglobin in the blood. Traffic exposures in St. Louis inside vehicles alone, for example, have been found to be over 30 ppm, or about twice the levels measured by the Continuous Air Monitoring Program station.[54]

As far as healthy humans are concerned, numerous experiments conducted under carefully controlled conditions have demonstrated that repeated exposures to low but significant amounts of carbon monoxide do not result in any permanent ill effect.[52]

The goal of 30 ppm, not to be exceeded for any 8-hour exposure period, includes some consideration of the persons within special groups, but is not unduly governed by the needs of these groups. Some researchers believe this goal should be as low as 5 ppm for 8 hours.[55]

OXIDANTS

Oxidant levels, as measured in urban atmospheres, record the results of a complex atmospheric interaction that apparently involves the primary air pollutants as reactants and catalysts. Photochemical smog is the term used to describe the resulting group of secondary air pollutants. Measured levels of urban air oxidants are compared in Table 6 with results from experiments using ozone under laboratory conditions. The complexity of urban-air-measured oxidants as compared to the simplicity of the laboratory-measured ozone must be kept in mind in assessing the effects attributable to oxidants.

Oxidants measured in urban atmospheres indicate effect levels of photochemical smog. Photochemical smog, as explained by Haagen-Smit,[66] is associated with a considerable increase in concentrations of ozone and other oxidant material. In smog formation sulfur dioxide, nitrogen dioxide, and aldehydes are believed to absorb ultraviolet radiation and react chemically with molecular oxygen to produce atomic oxygen (ozone). These reactions are irreversible for sulfur di-

Table 6. EFFECTS OF OZONE

Concentration, ppm	Observations[a]	Reference
0	Ozone considered radiomimetic - no safe level	56
0.01	Odor threshold of ozone	57
0.02 for 8 hr	Damage to tobacco leaves begins	58
0.03 for 8 hr	Significant damage to tobacco leaves	58
0.05	Nose and throat irritation threshold	56
0.05 for 1 hr	Damage to tobacco leaves begins	58
0.10 for 1 hr	Significant damage to tabacco leaves Pine tree needle tips burned	58
0.05	Threshold for eye irritation in sensitive people (ambient oxidant)	59
0.15[b]	Generally stated eye-irritation threshold for normal people (ambient)	
0.15 maximum allowable for 1 hr average (total oxidant)	Air quality goal for Study area (ambient oxidant)	
0.10	Reduction in oxygen consumption and blood oxygen tension (concentration) levels of emphysema patients, compared to effects on some patients breathing filtered air (ambient)	60
0.1 to 0.25 long term	Shortens life span, increases mortality of guinea pigs	61
0.10 for 8 hr	Definite symptomatic effects in sensitive people	57, 62
0.20 for 3 hr	Decrease of visual acuity	63
0.60	Cough irritation threshold, pronounced nose and throat irritation	63
1 for 1-1/2 hr	Coughing, irritation, severe exhaustion	64
3 to 12 for few hr	Lethal to small laboratory animals	65

[a] As determined from laboratory experiments using ozone except where otherwise noted. Ambient measurements are for "total oxidants."
[b] 0.25 ppm by the phenolphthalin method.

oxide and aldehydes, but the nitrogen dioxide reaction is cyclic unless the nitrogen dioxide is converted to nitric acid or is used up in organic reactions. In the sulfur dioxide reaction, the sulfur dioxide is oxidized to sulfur trioxide, with subsequent formation of sulfuric acid aerosol. Hydrocarbons and other organic pollutants react in varying degrees with the ozone and oxidant formed to yield compounds that cause eye irritation, vegetation damage, and reduced visibility.[66]

Most researchers agree that eye irritants are produced by photochemical oxidation of hydrocarbons in the presence of sunlight and nitrogen oxides. Researchers further agree that eye irritation is directly and consistently correlated with formaldehyde, acrolein, and PAN concentrations in the air. Ozone, the compound

with which most laboratory studies were made, constitutes the major proportion of oxidant in the atmosphere of most cities during all seasons. Concentrations, however, vary from season to season, being highest in the summer and fall as a result of the greater photochemical activity associated with the greater amount of sunlight. The percent ozone portion of oxidant concentrations is highest in the winter, often being 95 percent or more of the total oxidant. In the summer and fall, the relative proportion of ozone may drop to 80 percent or less because of the production of other oxidants in the photochemical reactions and the increased conversion of nitric oxide to nitrogen dioxide, the latter being an oxidant itself.

Eye irritation, although possibly not the most important effect of the constituents measured as oxidants, is the most troublesome and most commonly recognized effect in urban atmospheres. This major problem of photochemical-type air pollution varies greatly in the effects caused, not only because of differences in the sensitivity of the individuals affected but also because of variations in light, humidity, haze, and wind currents. Although the eye-irritation threshold level is usually placed at 0.15 ppm total oxidants as measured by the potassium iodide method, it appears that the total oxidant is not directly responsible for this effect.[67] It is attributed to specific chemicals associated with or among the measured oxidants, in particular the ozone-olefin reaction products.

The goal of 0.15 ppm, not to be exceeded for over 1 hour, is based upon the California standard. This goal measured as total oxidant will be equivalent to approximately 0.13 ppm ozone. As seen from Table 6, this concentration is somewhat higher than those concentrations causing significant damage to sensitive plants and producing symptomatic effects in sensitive people.

OXIDES OF NITROGEN

Seven oxides of nitrogen are known, but only nitric oxide and nitrogen dioxide are thought to play an important role in the formation and action of photochemical smog. Of the other five oxides, only nitrous oxide is normally present in significant concentrations (0.5 ppm) in the atmosphere. It is chemically inert at ambient temperatures. As described in the discussion of oxidants, the complex reactions that produce smog are initiated by the photolysis (breakdown) of nitrogen dioxide. In sufficient concentrations nitrogen dioxide is toxic to humans and vegetation; under some conditions it gives the atmosphere a yellowish-brown color.

Nitrogen oxides are formed primarily during combustion. In most communities power plants and motor vehicles are the primary sources, and space heaters, water heaters, and industrial processes contribute varying but lesser amounts. In the St. Louis area, motor vehicles emit an estimated 32 percent of the total nitrogen oxides and fuel combustion by power and industrial sources contribute about 55 percent. (See Volume II - Air Pollutant Emission Inventory.)

Nitric oxide and nitrogen dioxide are the only nitrogen oxides found in the atmosphere that reach concentrations sufficiently high to be of concern. Since nitrogen dioxide is five times as toxic as nitric oxide and is most active in promoting photochemical smog, most research on determining effects of nitrogen oxides has been based upon nitrogen dioxide. Table 7 shows some of its effects.

Since neither gas is very soluble in water, they pass through the upper respiratory tract and are hydrolized to nitric and nitrous acids in the high-humidity atmosphere of the alveoli. Nitrous acid is a potent mutagen, and nitric acid denatures human tissue and makes it leathery and brittle. These two acids promote the development of emphysema by destroying the lung alveoli and by decreasing resistance to other stresses such as airborne infectious microorganisms. A concentration of 3 ppm by volume of nitrogen dioxide for 1 hour may be serious enough to cause acute effects in sensitive people. Prolonged exposures to nitrogen dioxide concentrations of 0.5 to 1.0 ppm have been shown to be detrimental to the health of animals.

Data on phytotoxic effects indicate that exposure to 2 to 3 ppm by volume of nitrogen dioxide may cause acute damage to sensitive plants. Long-term exposure to concentrations of nitrogen dioxide below 1 ppm by volume may lead to growth suppression, chlorosis, and premature abscission of leaves. Exposures to 1 ppm by volume for 8 hours produce significant growth reduction, but no visible lesions.

Nitrogen dioxide absorbs light in both the ultraviolet and the visible spectrums. In sufficient concentrations it reduces the brightness and contrast of

Table 7. EFFECTS OF NITROGEN DIOXIDE

Concentration, ppm	Effect	Reference
0.1	Limit of acceptability for coloration effect in aerosol-free air with viewing distance of 10 miles.	68
0.25	Limit of acceptability for coloration effect in normal metropolitan area air with viewing distance of 10 miles when the visibility is 20 miles.	68
0.5 3 mo	Increased susceptibility to infection in mice by certain aerosolized bacteria.	68
<0.5 12 to 19 days	Significant growth reduction in tomato and bean seedings. No visible lesion damage. Chlorosis of leaves reported.	69, 70
1 to 3	Odor threshold.	68
2.5 7 hr or more	Bean, tomato, and nicotiana glutinosa leaves damaged with white lesions occurring.	71
3 4 to 8 hr	Pinto bean leaf damage.	71, 72
3.5 2 hr	Increased susceptibility to infection in mice by certain aerosolized bacteria.	73, 74
13	Nasal and eye irritation noticeable.	75

distant objects and imparts a yellow-brown color to the horizon sky and distant white objects. These coloration effects are enhanced as aerosol concentrations in the atmosphere decrease. Objectionable coloration effects can be expected to occur on days of good visibility (20 miles) with concentrations of about 0.25 ppm by volume of nitrogen dioxide.

At present authorities disagree as to whether reductions in hydrocarbon concentrations alone will produce the desired reduction in photochemical smog products.[68] In Los Angeles, for example, two eye irritation peaks have been observed. The earlier of the two peaks occurs at approximately 9 to 10 a.m. and seems to coincide with the maximum daily nitrogen dioxide concentration. The later peak occurs between about noon and 4 p.m. and corresponds to the peak total oxidant measurement. Some authorities believe that a reduction in hydrocarbon emissions alone may lead to a prolongation and intensification of the earlier peak. This presumably would occur because of a lack of hydrocarbons with which the nitrogen dioxide and other intermediate photochemical products react to form the materials causing the second eye irritation peak. Both hydrocarbon and nitrogen oxide emissions may thus have to be reduced to alleviate smog conditions that cause eye irritation.

No goal for nitrogen dioxide for the Study area has been chosen because of the uncertainty of authorities concerning the health effects of concentrations in the range of those occurring in the Study area. Adopting an ambient-air-quality standard such as that adopted by the California Department of Health (3 ppm for 1 hour = serious level) is considered unnecessary since this level is over 10 times higher than the 5-minute maximum levels recorded in St. Louis by the Continuous Air Monitoring Program. The mutagenic and denaturing effects of low concentrations of this pollutant in the lungs as well as the sky coloration and phytotoxic effects may, however, call for ambient-air-quality goals of less than 1 ppm.

EFFECTS OF PARTICULATE MATTER

Introduction

The effects of particulate matter vary widely, depending on particle size and composition as well as numbers. For example, less than 1 microgram per cubic meter of beryllium presents a health hazard, whereas inert dusts could be present in quantities several hundred times that without comparable danger. In their present stage of development, particulate collection and analysis do not make nearly all the tests desirable, but are limited primarily to finding total weight of particulate matter per unit volume of air. For this reason, many of the effects reported in Table 8 are based on the opinions of experts in the field of air pollution. These opinions relate to urban air, and the effects are attributed to or related to particulate matter combined with other pollutants in that environment. Reported visibility reductions and results from public opinion surveys, however, do stem from quantitative relationships.

The effects of particulate matter include contributions to reduced visibility, increased health effects (including cardiorespiratory diseases and eye irritation), increased vegetation damage, soiling, and increased materials damage.

Table 8 EFFECTS OF PARTICULATE MATTER

Concentration	Effect	Reference
$\mu g/m^3$		
25 to 50	Background levels	76
75 to 100	Considered satisfactory air quality by most people	
over 100	Increased mortality from all causes, increased mortality from chronic respiratory diseases	77
150 to 200	Considered dirty by most people	
over 200	Considered excessively dirty by most people	
100	Visibility reduced to about 5 mi	78
140	Visibility reduced to about 3 mi at humidity > 60%	78
75, geometric mean	Residential Air quality goal for Study area	
200, 99 percentile		
Cohs/1,000 lineal ft		
over 0.3	Increase in total morbidity and incidence of cardiovascular diseases among middle-class individuals 55 years of age or older	7
	Increased mortality from respiratory diseases among the middle socioeconomic class	8
0.4 60% relative humidity	Visibility reduced to about 9 mi	79
0.4 >90% relative humidity	Visibility reduced to about 3 mi	79
0.4	Air quality goal for Study area	
2.6 60% relative humidity	Visibility reduced to about 3 mi	79
tons/mi^2/mo		
5	Background level	
15	Considered satisfactory for residential areas	
10 3-mo average above background in all areas except those zoned heavy industrial.		
25 3-mo average above background in zoned heavy industrial areas.		
30	Considered dirty by most people	

Health-Related Effects

Health effects associated with airborne particulate matter vary with the particle sizes and the chemical activity of the pollutant, and its sites of toxic action. Since air pollutant effects are associated primarily with action upon the respiratory system, consideration of the mode of entry and action will be limited to that system. Particles larger than 10 microns in diameter are practically all removed in the nasal passages. Upper respiratory efficiency in removing particulate matter decreases as the size of particles decreases and becomes practically nil for 1-micron-diameter particles. The efficiency of particle removal is high in the pulmonary air spaces, being approximately 100 percent for all sizes above 2-micron diameter. Below this size, the efficiency decreases to a minimum at about 0.5 micron and then increases again as the force of precipitation by diffusion becomes more effective on these smaller particles. The percentage penetration of particles into

the pulmonary air spaces increases from practically zero at 10 microns to a maximum at and below 1 micron, where it is equal to the percentage of tidal air that reaches the lungs. The percentage of inhaled particles that are deposited in the pulmonary air spaces has a maximum value between 1 and 2 microns. The relative amount of particulate matter deposited and its distribution in the respiratory system, however, does change with breathing frequency and tidal volume. Upper respiratory trapping increases with faster breathing as the rate of inspired airflow increases. The amount of deep lung deposition of particulates increases with slow, deep breathing because of the larger amount of tidal air reaching the pulmonary air spaces and the longer transit time of air in the lungs.[80]

The effects of particulate matter deposited in the lungs depend upon the chemical and biological action that the material may have on the exposed cell tissue and the body's defense mechanisms. Acid mists, silica, and beryllium as well as certain other metals are especially damaging to the lungs and human health. Beryllium, which was not found in samples collected during the Study, is a serious health hazard. Certain carcinogenic materials, which also occur in particulate form, can be a serious health hazard. Measurements of benzo(a)pyrene, one of the potential cancer-causing air pollutants, made during the Study, showed the pollutant concentration in the St. Louis area to be comparable, in a general sense, with those in other United States cities of similar size and composition. The sample average was 10.2 $\mu g/1{,}000\ m^3$ during the winter of 1964, with the range between sites from 1.4 to 28.0 $\mu g/1{,}000\ m^3$. The United States urban average value is 5 $\mu g/1{,}000\ m^3$. In addition, samples analyzed indicated the possibility that other potential cancer-producing airborne particulates may be present in the Study area's atmosphere. In 1959 an abnormally high concentration of 54 micrograms of benzo(a)pyrene per 1,000 cubic meters, over 10 times the urban average, was recorded. Report Volume III, Air Quality Measurements, presents the benzo(a)pyrene data in detail with interpretation regarding occurrence and sources. Present knowledge of this pollutant is inadequate to explain the variation found in the Study area, but its occurrence emphasizes the need for continuing to measure the concentrations of this pollutant and supporting research to better define its importance in the environment. Most authorities agree that although a large proportion of the increased rate of lung cancer in cities can be attributed to the smoking habits of city dwellers, a certain part of the excess cancer rate in urban areas is due to air pollution.[81]

As mentioned previously, laboratory experiments with human subjects have demonstrated that particulate matter penetrating the pulmonary air spaces exerts additional effects when present with certain gaseous pollutants in the air. In other words, when the gas is adsorbed on the particulate matter, it has a greater detrimental effect than if it were present in its natural state.[82, 83] In addition, free soluble gases are largely absorbed in the upper respiratory tract, whereas gas adsorbed on particulates may pass through the upper respiratory tract and be deposited in the alveoli.

Vegetation Damage and Related Effects

Gaseous matter adsorbed or absorbed on particulate matter may also produce vegetation, animal, or materials damage. Vegetation damage can be caused by chemically inert particulate matter building up on the leaf until sunlight cannot

penetrate the layer. If the particles are not inert, damage may occur as the result of direct burning by acid, caustic, or other active droplets or by absorption of biologically injurious compounds. Animals eating pollutant-covered forage or forage having the pollutart within its leaves are particularly endangered. Fluoride damage to bones and teeth of cattle is an example of this type of effect.

Soiling

Particulates soil many surfaces and increase the costs of cleaning buildings, laundry, and dry cleaning. Figures 3 and 4, showing cleaning of the Old Post Office Building and an office building in downtown St. Louis, illustrate these effects. Damage to building exteriors caused by particulates and by gaseous compounds in the air decreases building life and increases building maintenance costs.

A study conducted in the upper Ohio River valley in 1959 and 1960 revealed important differences in the cost of four categories of cleaning in communities subjected to different levels of air pollution.[84] The activities examined were care of the exterior of homes, interior of homes, clothing, and hair and face. Three communities having distinctly different air quality, but similar weather and income levels were compared. With few exceptions, greater frequency of cleaning and maintenance operations was found necessary in areas of higher air pollution. Estimates of the costs of 28 household and personal chores (Table 9) show that a family living in air containing an average of 383 micrograms per cubic meter of suspended particulates spent from $47 to $829 per year more than a family living in air containing an average of 115 micrograms per cubic meter. The third city included in the study had an average air quality of 178 micrograms per cubic meter, and, as expected, the cleaning costs for its citizens were greater than those for the cleaner city and less than those for the dirtier city. The large range in cleaning costs is due to the differences in standards of living. The range is considerably less for any one selected standard of living. The table also shows an increase in laundry and cleaning costs of about 25 to 30 percent for the people living in the dirtier atmospheres.

Visibility

Visibility is reduced appreciably by particulate matter in the atmosphere. At relative humidities of approximately 70 percent or greater, visibility may be reduced primarily by water vapor. At lower humidities, the decreases in visibility are due primarily to the effect of particulate matter in the air. Of major importance in the relationship between air pollution and decreased visibility are particle sizes and numbers. Particles having approximately the same diameter as the wavelength of light (0.4 to 0.7 micron) reduce visibility more effectively per unit quantity than do other sizes - a fact related to light-scattering properties and total area available to block light. Burt,[79] using St. Louis, Missouri, data from 1954 through 1958, showed a semilog relationship between visibility and soiling index at 60 percent relative humidity (Figure 5). Day-to-day or other single-event predictions of coefficient of haze (Coh) values based on visibility, or vice versa, may be highly inaccurate, however, since the variables concerned cause a wide scatter of data.[79] In part, this lack of small-number correlation may be due to difficulties in making field measurements of visibility and particulate concentrations as well as the influence of the variable particle densities along any visibility measure

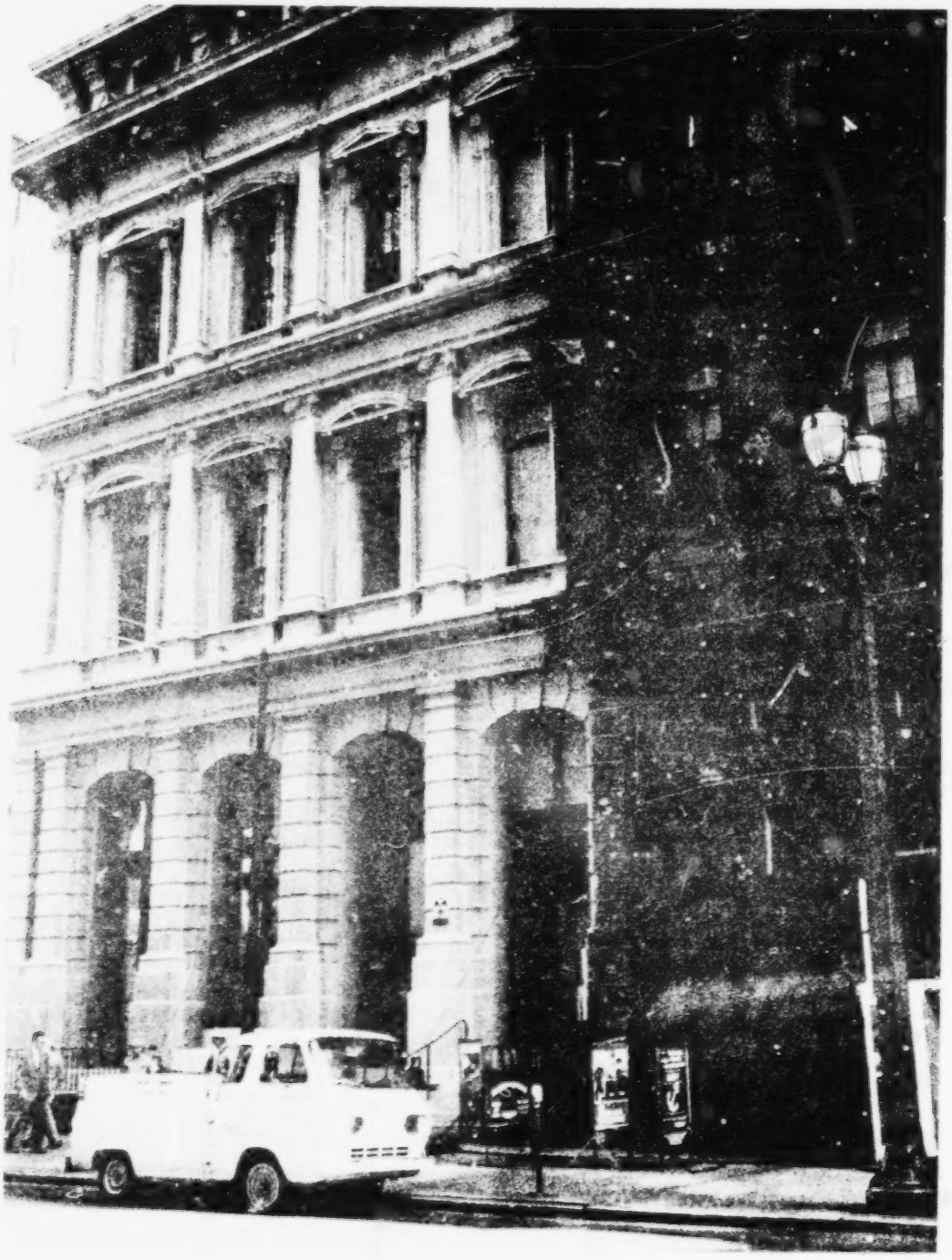

Figure 3. Post Office Building during sand-blast cleaning.

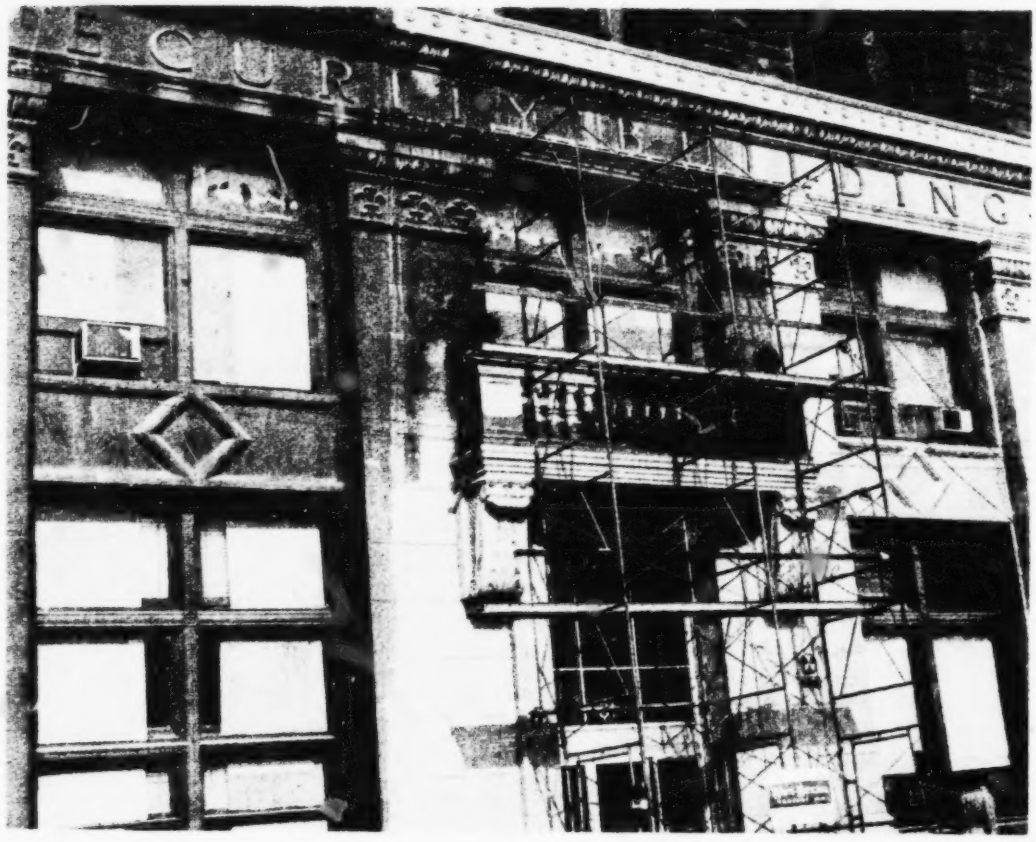

Figure 4. Office building during sand-blast cleaning.

ment trajectory. In spite of these difficulties, correlations based on long-term relationships have been determined for visual range and pollutant concentrations, both by calculations and experiment.[78] Figure 6 shows a corresponding range of visibility for specific water droplet and iron sphere sizes at various concentrations. This figure further emphasizes that for a fixed weight of particulates per cubic meter of air, the point of maximum visibility impairment occurs as particle diameters approximating the wavelength of light.[85]

Visibility trends are affected not only by air pollution control efforts, but also by general changes that occur in the community. An analysis made in Salt Lake City, Utah, utilizing number of hours with visibility of 3 miles or less due to smoke, shows a sharp rise caused by rapid industrial expansion during World War II. An investigation of visibility conditions in the Salt Lake Valley by the Utah State climatologist revealed that visibility was much better during the 1930's than during the years after World War II. Contrary to the experience at Salt Lake City, visibility has improved in many cities during these years as a result of conversion from steam to diesel locomotives and from coal to gas and oil for heating. This improvement in visibility pertains to the Study area also. As indicated in Table 10, visibility has improved the most during the winter months. The improvement reflects both regulatory activity and changes in fuel use.

Table 9. ADDED COSTS OF LIVING IN DIRTY ENVIRONMENT (DOWNTOWN STEUBENVILLE, OHIO, 383 $\mu g/m^3$ VERSUS UNIONTOWN, PA., 115 $\mu g/m^3$) FOR 28 ACTIVITIES, 1960

	Income group[a]	Per family	
		Do-it-yourself	Non-do-it-yourself
Inside maintenance	(1)	$ 29	$ 162
	(2)	44	227
Outside maintenance	(1)	21	49
	(2)	337	368
Laundry and cleaning	(1)	27	79
	(2)	129	186
Hair and Facial care		9	48
Totals, per family			
In private homes	(1)	86	338
	(2)	519	829
In apartments (no inside painting or decorating, no outside maintenance)	(1)	47	263
	(2)	158	423

[a] (1) Annual income under $8,000.
(2) Annual income $8,000 or more.

Table 10. PERCENT FREQUENCIES OF ALL VISIBILITIES LESS THAN 7 MILES AT WEATHER BUREAU AIRPORT STATION (ST. LOUIS)

Dates (month/year)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1/35 to 12/41	50	45	39	32	18	14	14	17	22	33	40	52
1/58 to 12/60	34	18	28	10	12	8	13	11	9	20	13	22

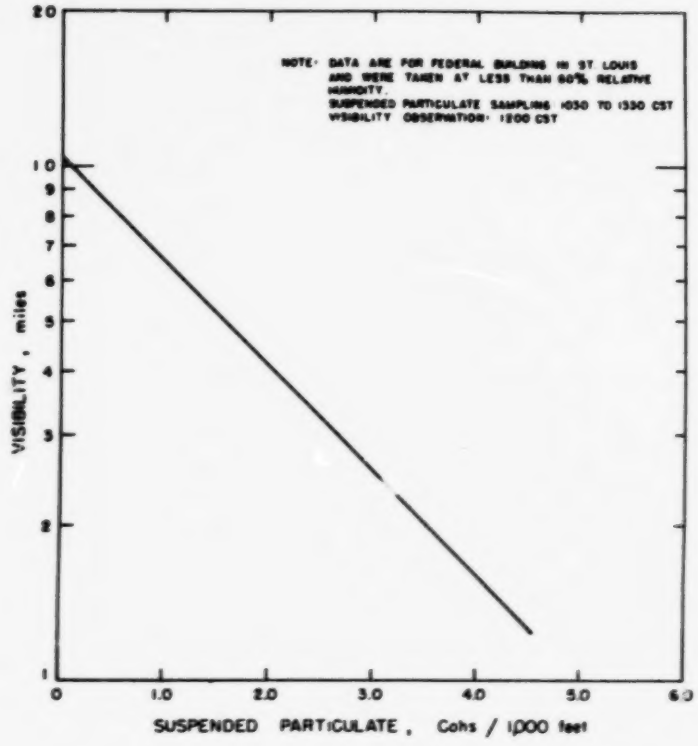

Figure 5. Soiling index versus visibility.

Figure 7 reports the hours per month that visibility is restricted at Lambert Field. These 10-year-average figures, varying from 55 hours in July to 160 hours in January, show that restricted visibility occurs a considerable portion of the time as a result of air-pollution-associated conditions.

Figure 8 is a wind rose of the wind directions and speeds associated with visibility of less than 3 miles at Lambert Field. Such visibility occurred during 11 percent of the total Lambert Field wind observations during the 1941 to 1950 period. Low visibility is associated primarily with low wind speed since calms and wind speeds less than 4 miles per hour occur during 37 percent of the low visibility observations. Such winds are reported for only about 15 percent of the total wind observations; therefore, about 27 percent of these low wind speeds (0.37 x 11/15) are associated with low visibility. In other words, low visibility can be expected to occur during about 3 out of 10 such low wind speed occurrences. Winds from the east to southeast, from the direction of the urban area, account for about 32 percent of the occurrences of low visibility, a higher percent than is associated with all three other quadrants together when allowance is made for the 37 percent low visibility that occurs during calms. Winds from the east to southeast quadrant occur only about 23 percent of the total time; thus low visibility does

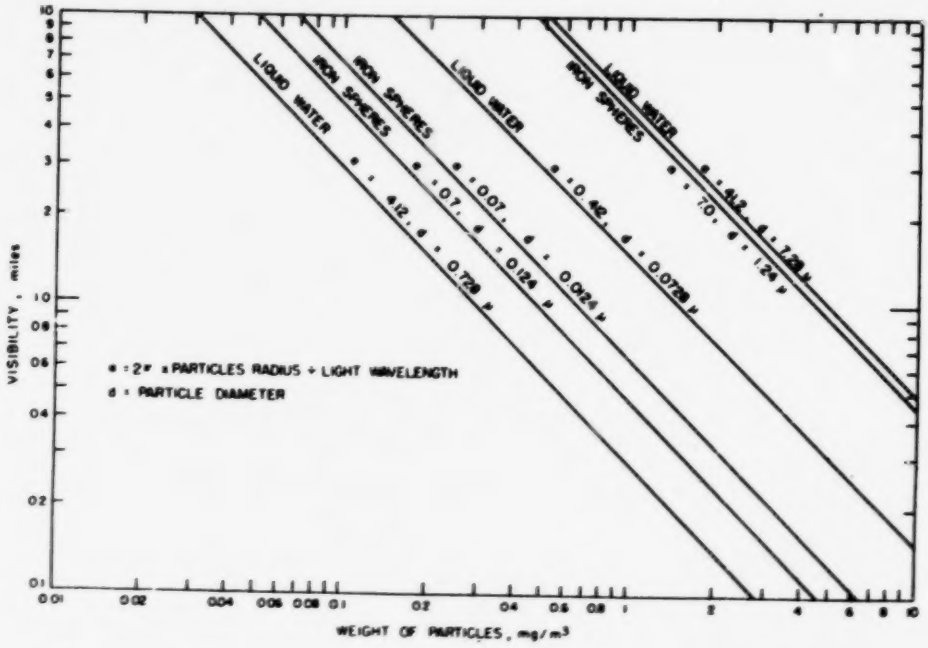

Figure 6. Range of visibility as a function of particle concentration by weight in the atmosphere.

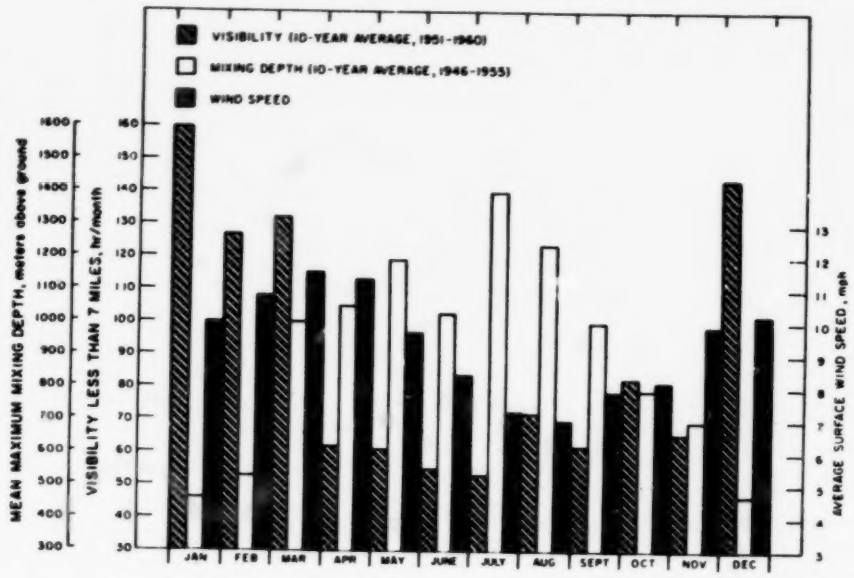

Figure 7. Visibility, mixing depth, and wind speed relationships at Lambert Field, St. Louis, Missouri.

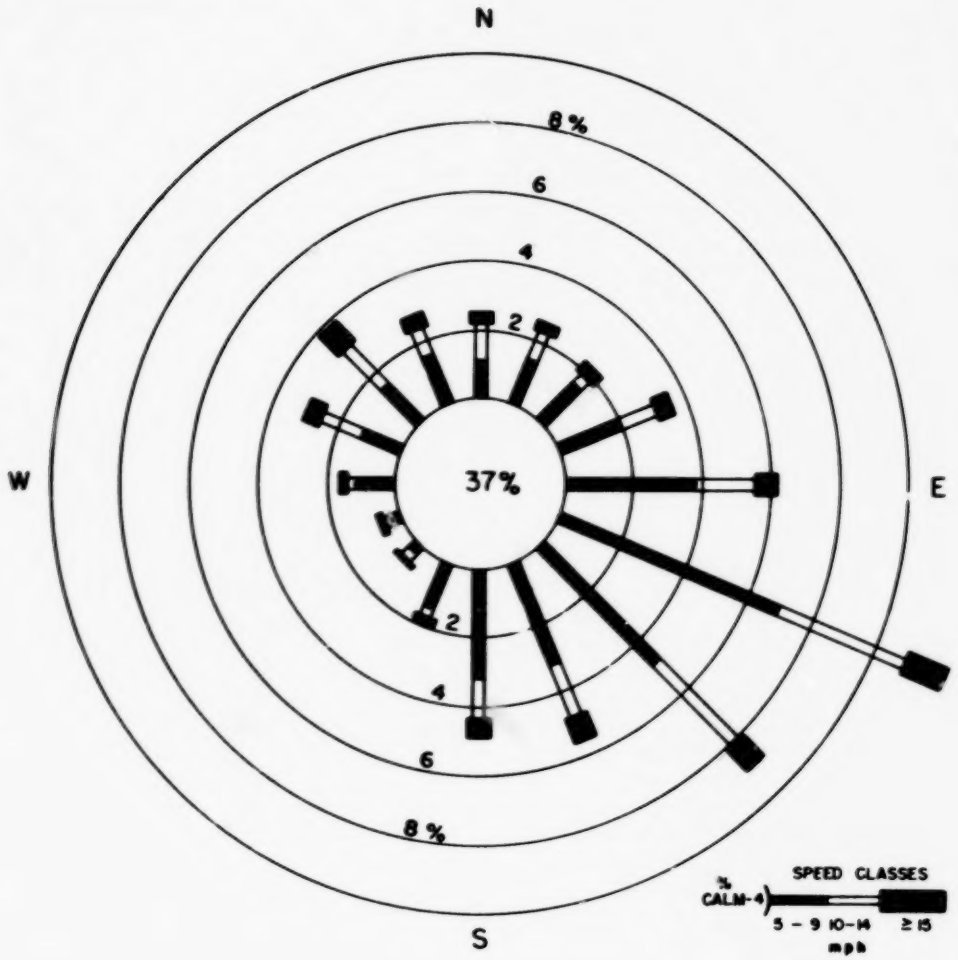

Figure 8. Wind rose for visibility less than 3 miles for all causes, Lambert Field, St. Louis, Mo., 1941-1950, percent frequency of occurrence.

occur more frequently than the general wind pattern would lead one to expect. This can be attributed to weather patterns and air pollutants from the metropolitan area.

Information on visibility at the Bi-State Parks Airport south of East St. Louis is not available. Since visibility is restricted by air pollutants at Lambert Field, reduced visibility can be expected to be more frequent at the Bi-State Parks Airport because of the greater frequency of low wind speeds at its location, its proximity to many major pollutant sources, and its location within the St. Louis - Cahokia Bottom area of high inversion frequency.[87]

Decreased visibility levels cause a direct economic loss when airports must be closed because of limited visibility. Three miles is the visibility distance needed for aircraft to land by visual approach. Instances of air-pollutant-caused reduction of visibility causing disruption of air service at Lambert Field have been reported by the Weather Bureau Station situated there. Reduced visibility is also reported to have significant effects on people who find their view of some cherished scene obstructed by air pollutants.

One of the criteria for particulate goals in the Study area is the 3-mile visibility needed by aircraft for visual landing approach. The goal of 200 micrograms per cubic meter not to be exceeded over 1 percent of the times would, according to present knowledge, correspond with the 3-mile sight distance when the relative humidity is below 70 percent (See Figure 6).

ODORS

The effects of odors are not limited to nuisance conditions; they also include human physiological effects such as nausea and psychological stress. Odors can result in economic effects because people tend to leave odorous areas. Odor problems in the Study area are documented in Volume IV, Odors - Results of Surveys. Some severe odor problems and an odor episode are reported in that volume. The downtown area of St. Louis is subjected to a pervasive odor that permeates hotel rooms, clothing, and certain items of merchandise. Persons visiting the area detect the odor on their clothing long after they have left the St. Louis area. Some merchants in the area have considered the installation of special filtering devices to remove the odorous material from the air as it comes into the buildings.

The report, Public Awareness and Concern With Air Pollution in the St. Louis Metropolitan Area,[88] indicates that 53 percent of the respondents who said there was air pollution in their neighborhoods defined air pollution as odors. Odors were consistently the highest definitional item for air pollution. The same report also indicates that 46 percent of all respondents in the Study area are bothered by air pollution. Although the effects of air pollution on cleanliness are most frequently mentioned, Table 22 of this same report indicates that 15 to 25 percent of the people feel the value of their homes is affected and 20 to 35 percent feel that the reputation of their residential area is damaged by air pollution. The report goes on to point out that those individuals having lung trouble, heart trouble, or allergies are more likely to indicate that they are bothered by air pollution.

Public awareness of odors caused by motor vehicle exhaust is reported in Table 27 of Public Awareness and Concern With Air Pollution in the St. Louis Metropolitan Area.[88] This table shows that in St. Louis County, motor vehicle exhaust is named more frequently (approximately 25 percent) as a definitional item for air pollution than it is in any of the other political subdivisions of the Study area.

A review of complaint records, reported in detail in Volume I, reveals that objectionable odors cause more complaints than any other type of air pollution. The good agreement among the several reports and surveys indicates that people notice the effect of odors more than those of any other type of air pollution in the Study area.

ASTHMA - A PILOT STUDY

There have not been any recent community-wide epidemiological studies or investigations relating air pollution to effects on human health in the St. Louis Metropolitan Area. In 1964, however, the Public Health Service, Division of Air Pollution, Field Studies Branch, initiated a pilot project study to investigate the occurrence of asthma attacks in the St. Louis area and their relation to air pollution. Because the study is still in progress, the data relating to asthmatic attacks presented in this report are only a fraction of those planned for the above-mentioned study.

The pilot project data consisted of records of asthma patients admitted or treated during 1961 and 1962 in the emergency rooms of the two East St. Louis hospitals, St. Mary's and Christian Welfare. During the 2-year span, 739 cases of acute asthma attacks were recorded in the emergency room logs of the two hospitals. These cases accounted for 2.1 percent of the total number of emergency room visits recorded. The maximum number of asthma patients reported in any 1 day during this time was six.

The seasonal distribution of asthmatic patient visits recorded during both 1961 and 1962, as shown in Figure 9, indicates a significant increase during the months of September, October, and November. Similar autumnal increases in the frequency of asthmatic attacks have been observed in other cities.[89, 90] Suggestions explaining the cause of these increases include: onset of cold weather with accompanying metabolic adjustments; resuspension of settled allergens in the home heating systems at the beginning of a heating season; increased atmospheric stagnation during this period with associated increases in pollutant levels;[91] and prevalence of mold spores, particularly those associated with decaying vegetation.[89]

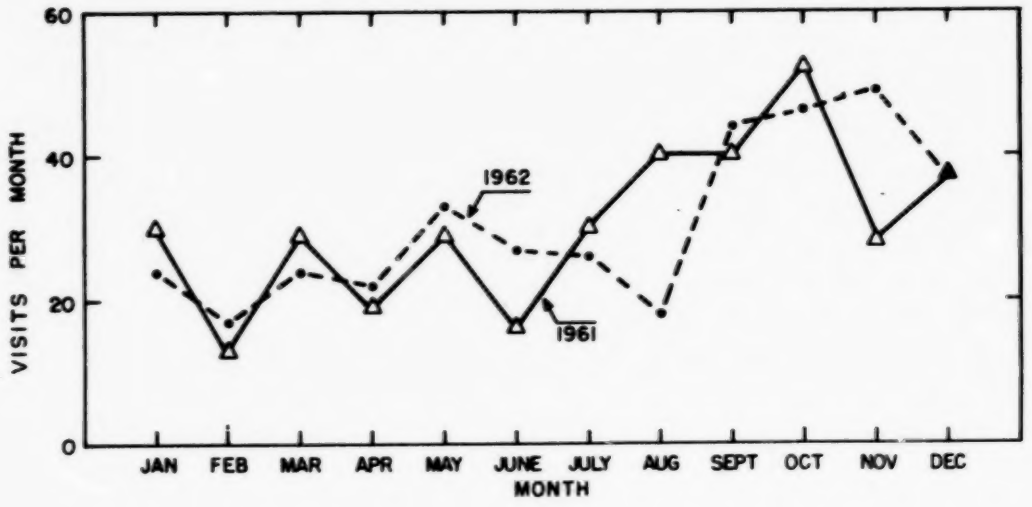

Figure 9. Emergency room visits by asthma patients in East St. Louis hospitals during 1961 and 1962.

AEROALLERGENS

Pollen grains discharged into the atmosphere by weeds, grasses, and trees are the major cause of hay fever; certain molds, spores, and plant rusts also add to the problem. As measured by the American Academy of Allergy method, 25 to 30 pollen grains per cubic meter of air are considered sufficient to cause a reaction in allergic individuals.[92] Estimates of the proportion of populations affected by hay fever in various areas of the United States vary from 2 to 10 percent.[92-94] An estimated 100,000 people in the St. Louis Metropolitan Area suffer from hay fever. Most patients have an uncomplicated type of hay fever in which the symptoms disappear at the termination of the pollen season, but sinusitis, catarrh, bronchitis, bronchial asthma, and both acute and chronic dermatitis may develop from ragweed sensitization.[92] The most important effect is the development of bronchial asthma, which increases debilitation and decreases life span in cases where sensitivity has extended to the mucous membranes of the lungs.

Hay fever is most often seasonal in character. Spring hay fever (March to June) is associated with tree pollens; summer hay fever is attributed to grass pollens; and autumn hay fever is usually due to weed pollens. August and September are the worst hay fever months in the St. Louis area, with the greatest part of the problem caused by ragweed pollen. This weed, although not an aggressive invader, rapidly takes over neglected land and land that has been denuded or disturbed, and thus begins a succession of plant types that ultimately ends with grass.

Each ragweed plant may produce millions of pollen grains. Although most pollen pollution occurs in the immediate area of origin, pollen grains, because of their small size (10 to 50 microns) and buoyancy, may be carried long distances by the wind. Actual clouds of pollen are known to occur. In 1873, pine pollen from 400 miles away deposited in St. Louis made the ground appear as though it had been sprinkled with sulfur.[92] Pollen clouds may explain increases in hay fever symptoms after sunset even though ragweed plants usually release their pollen early in the morning. With sunset, cooling of the air concentrates clouds of pollen at ground level.

Although local ragweed control programs have been found effective in some areas, other ragweed control programs have proved ineffective because of transport of pollen from nearby areas having no ragweed control.[94] Eradication of ragweed in a limited area may not, therefore, reduce hay fever incidence. An approach toward solution of the problem seems to be control on a metropolitan-wide basis through (1) mowing, (2) use of soil sterilizers, (3) use of herbicides, and (4) maintenance of ground cover.

Such a program should be accompanied by research that would evaluate results; determine threshold response levels; determine the importance of various pollens, spores, molds, and plant rusts; and establish the degree of control needed to reduce hay fever incidence by known amounts.

VEGETATION DAMAGE

The effects of air pollution have long been known to cause serious damage to vegetation. For example, agricultural losses from photochemical smog in the belt from Washington, D.C., to Boston are estimated at some $18 million a year. An additional annual loss of approximately $10 million is attributed to this same

pollutant in California, and the characteristic markings of smog have been found on vegetation near practically every metropolitan area in the country. Other commonly occurring pollutants such as sulfur dioxide result in additional losses. When air quality standards and goals are being established, the vegetation effects associated with these pollutants should be considered both from an economic and an aesthetic standpoint.

Fluoride Effects on Vegetation

The concentration of gaseous fluoride required to cause injury in susceptible plants is exceedingly low. For example, gladiolus plants incur appreciable injury in a few days when exposed to concentrations of 1 to 2 parts per billion.[95] A list of some of the more susceptible species is presented in Table 11.

Table 11. SENSITIVITY OF SOME CULTIVATED PLANTS AND FARM ANIMALS TO INJURY BY HYDROGEN FLUORIDE[a]

Sensitive class 1	Intermediate class 2	Resistant class 3
Plants[b]		
Gladiolus	Alfalfa	Cabbage
Apricot	Barley	Cotton
Prune	Buckwheat	Dandelion
Sweet potato (some varieties)	Carrot	Squash
Corn	Clover	Sweet pea
Grapes (some European varieties)	Lettuce, head	
Peach	Sweet potato (some varieties)	
Buckwheat	Wheat	
Animals[c]		
Cattle	Swine	Horses
	Sheep	Poultry

[a] Data from references 95 and 96.

[b] Concentrations required to cause slight injury to plants in 7 to 9 days:
Class 1 = 5 ppb or less
Class 2 = 5 to 10 ppb
Class 3 = more than 10 ppb; higher concentrations require proportionally less time.

[c] Rations containing fluoride concentrations that exceed the following values may result in clinical fluorosis:
Class 1 = 30 to 50 ppm
Class 2 = 70 to 100 ppm
Class 3 = greater than 100 ppm (poultry 1,200 to 2,400 ppm).

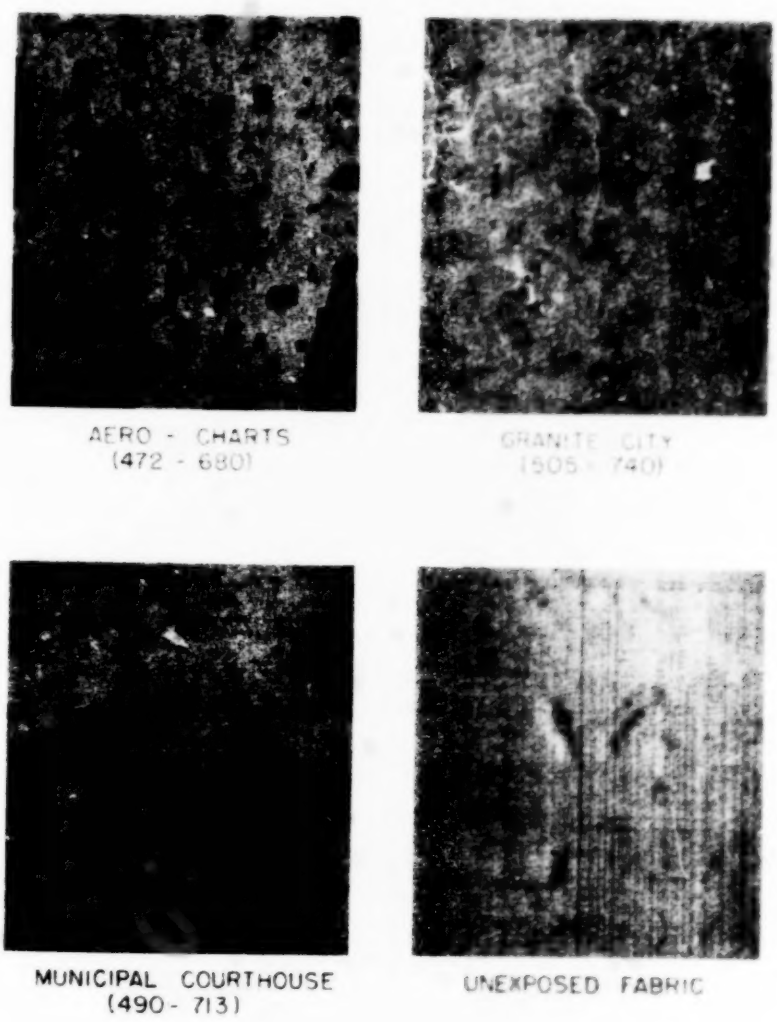

Figure 18. Effects on nylon fabric exposed to ambient air (June 1963 - April 1964).

EFFECTS OF AIR POLLUTION ON PROPERTY VALUES

Air pollution is generally assumed to depress property values; however, very few attempts have been made to measure this relationship quantitatively. As yet no commonly accepted hypothesis exists for the mathematical form that this relationship might take. Dr. Ronald G. Ridker of Washington University started work toward defining this mathematical relationship in 1963. Dr. Ridker used his region's Air Pollution Study air-quality data and census tracts in which single-family housing units comprised at least 60 percent of the total housing and the population density was at least one person per acre. He then applied the following variables to this census tract population sample: (1) air pollution as measured by soiling, (2) time

The principal industries or processes responsible for atmospheric fluoride emissions are: (1) aluminum reduction, (2) smelting of ferrous and nonferrous ores, (3) ceramics, and (4) phosphate reduction and phosphate fertilizers. In the aluminum industry the fluorides stem primarily from the molten cryolite bath. In the others they arise from impurities in the raw materials.

Exposure to fluorides causes a characteristic tissue collapse. Gaseous fluorides are presumed to enter the plants through openings in the leaves and, once inside, to be transported to the edges of the leaves along with the normal flow of water. When the accumulation of fluorides in the tips or edges of the leaves exceeds a certain concentration, the tissue collapses, dries out, and usually develops a reddish tan or deep brown color. Continued exposure causes the injury to progress inward from the edges of the leaves.

Because of the cumulative effect of gaseous fluorides, establishing air quality goals for these materials is difficult. In addition, the extremely low levels encountered in the atmosphere present many analytical problems.

Fluoride Effects on Farm Animals

Damage to farm animals as a result of atmospheric fluoride pollution involves primarily those animals that graze on contaminated forage. This contamination may result from absorption of gaseous fluorides by the forage, deposition of particulate fluorides on the leaves, and/or absorption from the soil. Fluoride uptake from the soil by vegetation, however, is generally slight even in the presence of high concentrations because fluorides are relatively insoluble.[95]

The effects of fluorides on farm animals are cumulative. Cattle are the most susceptible, with sheep, swine, horses, and chickens decreasingly susceptible in the order named. In animals with immature teeth dental mottling is an early sign of fluorosis. If the fluoride intake is high, an abnormal growth in the bones of the legs, jaw, and ribs may occur. Advanced cases of fluorosis are characterized by lameness, weight loss, lowered fertility, bone lesions, retarded growth, and reduced milk production.[97]

Fluorosis may be prevented by reducing the fluoride in the daily total ration of cattle to 30 to 50 ppm and that of sheep and swine to 50 to 70 ppm.[96] Since the quantities of fluoride present in the rations depend on the ambient air concentrations, any air quality goals established for fluorides should be low enough to ensure the production of acceptable forage crops.

Sulfur Dioxide

Because of the severe damage it causes in certain areas and its widespread distribution, sulfur dioxide has been studied more intensively than any other single pollutant. Large quantities of this material are released by the combustion of fossil fuels (especially high-sulfur coal, and to a lesser but still significant degree from fuel oils). The smelting of sulfide ores and the manufacture of sulfuric acid also produce large quantities of this gas, which is emitted to the atmosphere, unless proper control equipment are employed.

Sulfur dioxide injury to vegetation can be divided into two distinct types, acute and chronic. Acute injuries are characterized by the killing of sharply defined marginal or interveinal areas of the leaves. Following exposure, the leaves take on a dull water-soaked appearance. Subsequently, they dry up and usually bleach to an ivory color; some, however, turn brown or reddish brown. Chronic injury does not produce the leaf collapse observed in connection with acute injury, but bleaching occurs; and microscopic examination reveals cellular destruction. Injured areas of the leaves never recover, but the uninjured areas quickly and fully regain their functions; and new leaves develop normally.

Much work has been done on the effects of sulfur dioxide on crops of economic significance, and from these investigations formulas have been developed to predict yield losses resulting from exposure to this pollutant. These formulas take into account both concentration and length of exposure.[97] The results of investigations such as these together with the establishment of sulfur dioxide threshold response levels for various species of plants make it possible to establish air quality goals for such plants with a reasonable degree of confidence.

Photochemical Smog

Injury to leafy vegetables and field crops from photochemical smog was first documented in 1944 in the Dominquez area of Los Angeles. This injury is now known to occur throughout the United States in most metropolitan areas.[98] Symptoms of this type of plant injury include silvering, glazing, bronzing, and sometimes necrosis of the lower leaf surface. The under-surface glaze on young leaves is only one aspect of a complex of symptoms now recognized to be associated with photochemical smog. Leaf injury has been associated with periods of high air pollutant concentrations when reduced visibility and human distress are reported[71] and particularly with elevated oxidant measurements (levels above 0.05 ppm may mark tobacco leaves).[99] In 1952 it was demonstrated that typical "oxidant" damage was produced by complex chemical compounds resulting from the reactions of nitrogen dioxide, olefins, and air in the presence of ultraviolet light.[82] Within the photochemical complex are a number of known plant toxicants such as ozone (although ozone injury typically develops on the upper leaf surface[71]), peroxyacetylnitrate,[83] and the oxides of nitrogen.[68]

Serious damage occurs to ornamental shrubs and plants and to leafy vegetable and forage crops such as alfalfa, spinach, parsley, and celery. Exposure to photochemical pollution reduces tomato yields, retards cereal growth, injures cotton foliage, reduces alfalfa hay protein content, and reduces plant growth rates.

Ethylene

Ethylene occurs in the exhaust gases from combustion processes, including those of automobiles. Ethylene damage to a few highly sensitive plants, most notably to orchids, has been observed in many areas of the country. Exposure to concentrations as low as 2 parts per billion for 24 hours results in premature aging of certain portions of the orchid bloom. Such damage renders these flowers almost worthless on the commercial market.

Miscellaneous Pollutants

Numerous other pollutants may cause damage to vegetation, but the concentrations of these materials normally found in the atmosphere are generally not sufficient to be of significance. The rare occasions when they do occur in significant amounts are usually the result of a spill of some type - industrial or other. Among the contaminants in this category are chlorine, hydrogen chloride, ammonia, hydrogen sulfide, and formaldehyde.

VEGETATION DAMAGE IN STUDY AREA

Historical Development

Among the early published reports concerning the damaging effect of air pollution on vegetation in the St. Louis area were those that appeared in the Missouri Botanical Garden Bulletin during the 1910's, 20's, and 30's.[100] These articles described severe injury resulting from concentrations of smoke, soot, and sulfur dioxide in the atmosphere. Eighteen varieties of plants were listed as being seriously affected by atmospheric pollution in the November 1917 issue of the Missouri Botanical Garden Bulletin.

In June 1924, the Garden published a growth zone map, which showed the city divided into three zones having different levels of air pollution. A short list published with this map indicated those plant species most likely to survive in the general areas of each of the three zones.[100] A radial gradient of diminishing effect was easily discernible from the center of the city to the surrounding country. Kentucky bluegrass, American red cedar, and the lily were among the plants that could not survive in the more highly polluted areas. Because of this situation the Garden found it necessary to grow all of its display plants at Gray Summit growing station some 30 miles southwest of the city.

Following the enactment of the smoke control ordinance, conditions improved, and by 1945 many species of vegetation could be grown in the city again.

Since the end of World War II the metropolitan area has expanded in size and increased in complexity, and the variety of products manufactured has also expanded. This growth has caused new pollutants to be released to the atmosphere and has increased the levels of many of the existing pollutants. The principal gaseous pollutants of importance in vegetation damage are ethylene, fluorides, sulfur oxides, hydrogen sulfide, hydrocarbons, nitrogen oxides, and photochemical reaction products including oxidants such as peroxyacetylnitrate (PAN). The increasing concentrations of these various substances has once again resulted in increased deleterious effects to vegetation. As evidence, Dr. Edgar Anderson of the Missouri Botanical Garden has reported that attempts to grow Korean lespedeza (a plant used for ground cover on right-of-ways) in and near the center of the metropolitan area have been unsuccessful and attributes the problem to air pollution.

Over the past several years repeated instances of orchid damage have been observed by Mr. Robert J. Gillespie, Professor of Biology, Meramec Community College. Disfigurement of the flower's lower leaf division occurs most frequently in November and December, especially during or immediately after periods of heavy fog and smoke. The condition is seldom observed by growers in the rural areas away from the city.

E. P. Hume, a horticulturalist from Southern Illinois University, reported in June 1966 that over the past 3 years he had noted severe damage from air pollution to ornamental plants in the East St. Louis area. Plants most affected are the Chinese elm, tree of heaven, empress tree, and all the members of the legume family that were observed.

The injuries sustained were identical to injuries caused by certain growth-regulating hormones when used in toxic quantities. The causal factor attacks the terminal growth, often the tip leaf on a branch, or the top leaflets of a compound leaf. Growing points may be injured or killed, and similar damage to side branches, starting from below, may also take place. Repeated injury usually results in plant death.[101]

Some sulfur dioxide damage was observed and reported in the Interstate Air Pollution Study Phase I Report. Other air-pollution vegetation damage was reported, but was not verified by the project staff.

Tobacco Plant Oxidant Study

A study to define plant injury due to oxidant exposure in the St. Louis Metropolitan Area was conducted from April 29 to October 15, 1965. This study showed that oxidant, presumably of photochemical origin, occurs in the St. Louis area in sufficient concentrations to produce markings on sensitive vegetation (Figure 10).

Figure 10. Markings on sensitive vegetation.

Observations were made at 14 sites (Figure 11). Tobacco plant oxidant damage occurred most frequently at the three central metropolitan sites (those within East St. Louis and St. Louis cities), probably because of the dense traffic in these areas. Leaf damage was reported at each of these three sites on 20 or more occasions. Since all sites reported damage on at least two occasions, damaging oxidant concentrations occur throughout the Study area (Figure 11).

Observed leaf damage is apparently associated with sudden increases in oxidant levels measured by the USPHS Continuous Air Monitoring Program station the day

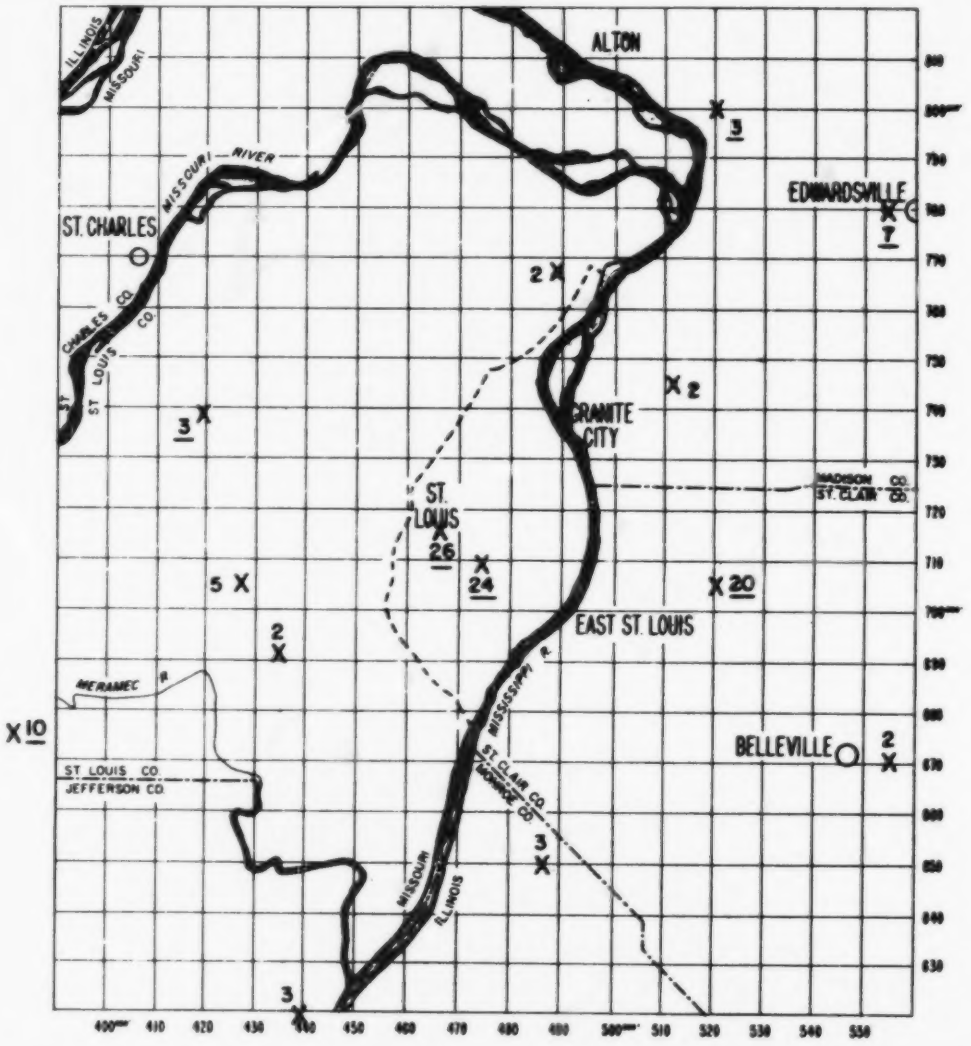

Figure 11. Locations of tobacco leaf damage observations. Underlined figures indicate 4- or 5-month observation period, other figures 2-month observation period. Numbers report number of times leaf damage occurred.

before the observable damage occurs. Table 12 shows that the sum of total hourly daytime (8 a.m. to 4 p.m. Central Standard Time) averages of oxidant concentrations increased significantly during the day before observed damage. This sum for

Table 12. OBSERVED DAMAGE VERSUS CONTINUOUS AIR MONITORING PROGRAM OXIDANT MEASUREMENTS IN MAY AND AUGUST 1965[a]

	Levels of oxidant - sum of hourly daytime averages, ppm			Change in sum of hourly daytime averages, ppm	
(1) Date of observed damage	(2) 2 days before (1)	(3) 1 day before (1)	(4) day of (1)	(3) to (2)	(4) to (3)
May 2	x[b]	35	x	x	x
5	25	30	25	5	-5
12	30	55	40	25	-15
14	40	45	x	5	
19	x	x	x	x	x
22	x	40	40	x	0
25	30	20	15	-10	-5
31	40	50	35	10	-15
May avg	33	39	31	7	-8
June 3	20	35	55	15	20
10	25	90	80	65	-10
13	40	50	40	10	-10
18	45	55	50	10	-5
24	30	50	30	20	-20
28	50	25	x	-25	x
June avg	35	51	51	16	-5
July 5	35	70	45	35	-25
11	25	30	40	5	10
18	30	40	50	10	10
25	40	x	45	x	x
29	45	25	30	-15	5
July avg	35	41	42	9	0
Aug 10	15	25	35	10	10
16	35	55	45	20	-10
20	x	x	x	x	x
24	25	50	30	25	-20
30	20	25	30	5	5
Aug avg	24	39	35	15	-4

[a] The average of the sums of daily hourly averages (8 a.m. to 4 p.m. Central Standard Time) was 32 ppm for May, 42 for June, 37 for July, and 32 for August.

[b] x indicates no data.

the day before observed damage was also significantly greater than the monthly average in most cases. Decreases in the sum generally occurred the day of and the second day before the observed damage, with the sum of the second day before usually being considerably lower than the sum of the day of the observed damage.

Several cooperating growers noted the appearance of similar injury patterns on other greenhouse crops simultaneously with the injury of the sensitive tobacco plants. Especially noted as having developed typical oxidant damage lesions were geranium, gloxinia, begonia, and periwinkle plants.

MATERIALS DETERIORATION

During the Study several activities were conducted to determine the effects of air pollution on steel plates, cotton fabrics, and nylon fabrics. These studies generally showed that the severity of effects coincided with the sulfur oxides and particulate air pollutant distribution pattern over the metropolitan area.

Steel Corrosion Study - 3-Month

Figure 12 shows the geographical distribution of steel panel exposure sites used for a study from December 1964 through February 1965 and the resulting 3-month corrosion losses. Comparison of these losses with high sulfur oxides and particulate air pollutant levels shows that increased corrosion generally occurred in the areas with higher pollutant levels. Comparison between the corrosion level at a suburban site west of the metropolitan area and that in the highest pollutant area showed an increase of approximately 240 percent. Figures 13 and 14 show that statistical correlations of corrosion with sulfur dioxide levels and sulfation levels were quite high.

Steel Corrosion Study - 16-Month

Figure 15 shows the locations of 33 of the 35 exposure sites used for this study and their corresponding 2- and 16-month weight losses due to corrosion. For the 16-month period, above-average corrosion occurred primarily in south St. Louis and in Illinois, along the Mississippi River from Alton to below East St. Louis. Little difference was noted between St. Louis County and St. Louis City residential-commercial areas by the end of the 16-month exposure period.

A significant relationship was found between corresponding sulfation rates and losses from corrosion (see Figure 16). Dustfall data compared in a similar manner did not show a similar correlation. The conclusion is that gaseous pollutants cause more damage than particulate pollutants to metals in the Study area.

Because of the "protective" nature of rust coatings, atmospheric corrosion rates generally decrease with the length of exposure time. When plotted on graph paper, these rates assume a form between parabolic and logarithmic functions. The maximum protection offered by the rust coating takes several years or more to develop fully. During this period, and especially in the early stages, seasonal, meteorological, and air pollutant variations markedly influence corrosion rates. As exposure time increases, the influence of these environmental factors becomes less and less, as demonstrated graphically by Figure 17, which shows the composite curves for time versus weight loss for the St. Louis County residential-commercial

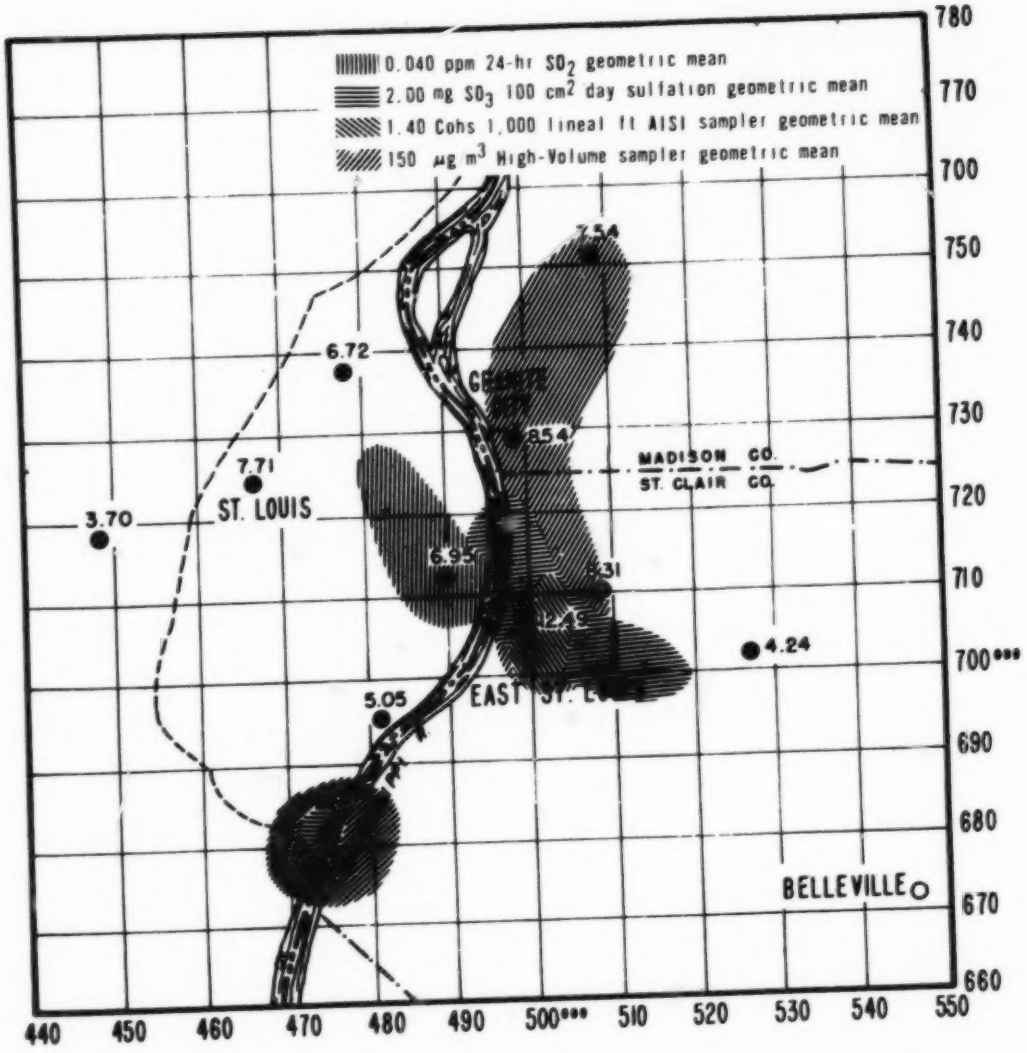

Figure 12. Three-month mean corrosion losses (Dec. 1964 - Feb. 1965) and high mean pollution levels (July 1963 - July 1964).

sites (9 sites east of Bypass 66 and 67 Highway) and for the St. Louis City residential-commercial sites (9 sites). The corrosion rates for the two types of sites are significantly different (at the 99 percent confidence level) during the early stages of corrosion, but at the end of 16 months, the protective coatings provide equal protection against the pollutants at both types of sites. This relationship is not true for sites in the higher pollution areas. The composite high-pollution (industrial) curve shows a higher initial weight loss from corrosion and a consistently greater corrosion rate than that determined for the residential-commercial areas. After 16 months, panels exposed in the industrial areas had lost 35 percent more weight than those exposed in the residential-commercial areas.

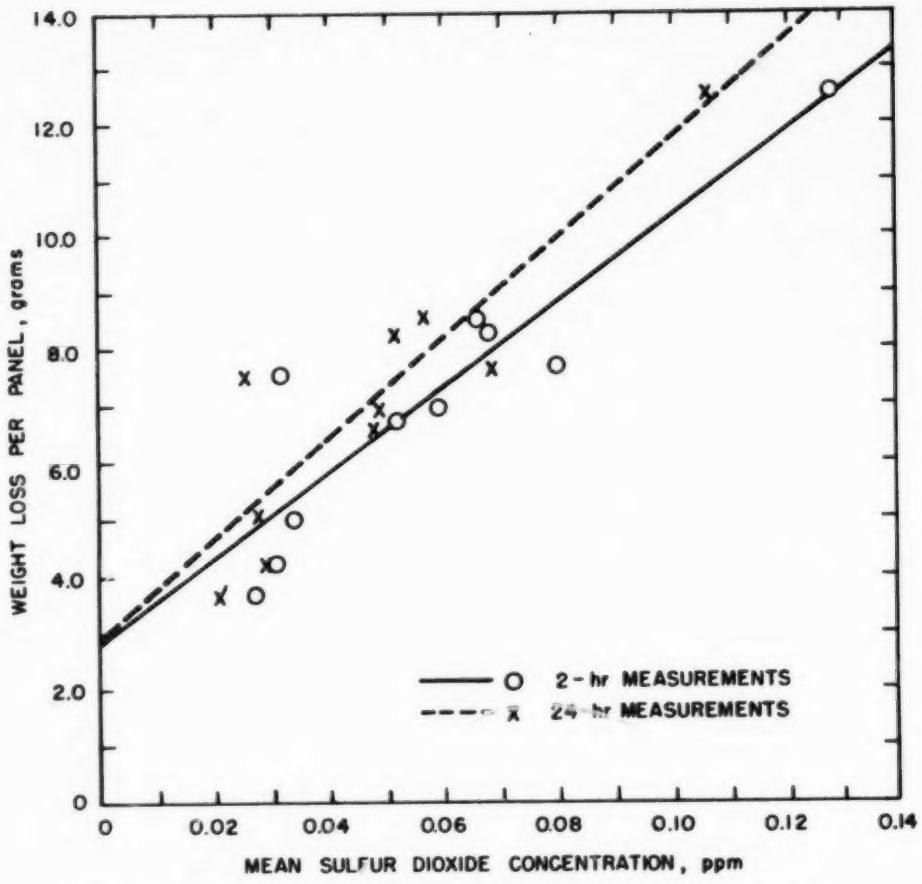

Figure 13. Relationship between corrosion of mild steel and corresponding mean sulfur dioxide concentration for a 3-month exposure at 10 metropolitan St. Louis sites (Dec. 1964 - Feb. 1965).

Effects on Exposed Nylon Fabric

As part of the Interstate Air Pollution Study effects-measurement program, nylon panels were mounted on small wooden frames and exposed. The nylon cloth panels consisted of Dupont* nylon 66, woven into a fine 210-mesh material of a type ordinarily used as a filter material. The panels were set out in mid-June of 1963 and were observed monthly. After 2 months of exposure, the panels exhibited varying degrees of dirtiness, a few runners had developed, and chemical (rust-like) stains were noted. After 4 months, runners had developed on five of the panels. At the end of 8 months, fine pinhead-size perforations began to appear in the panel

*Mention of company or product names does not constitute endorsement by the Public Health Service or the Department of Health, Education, and Welfare.

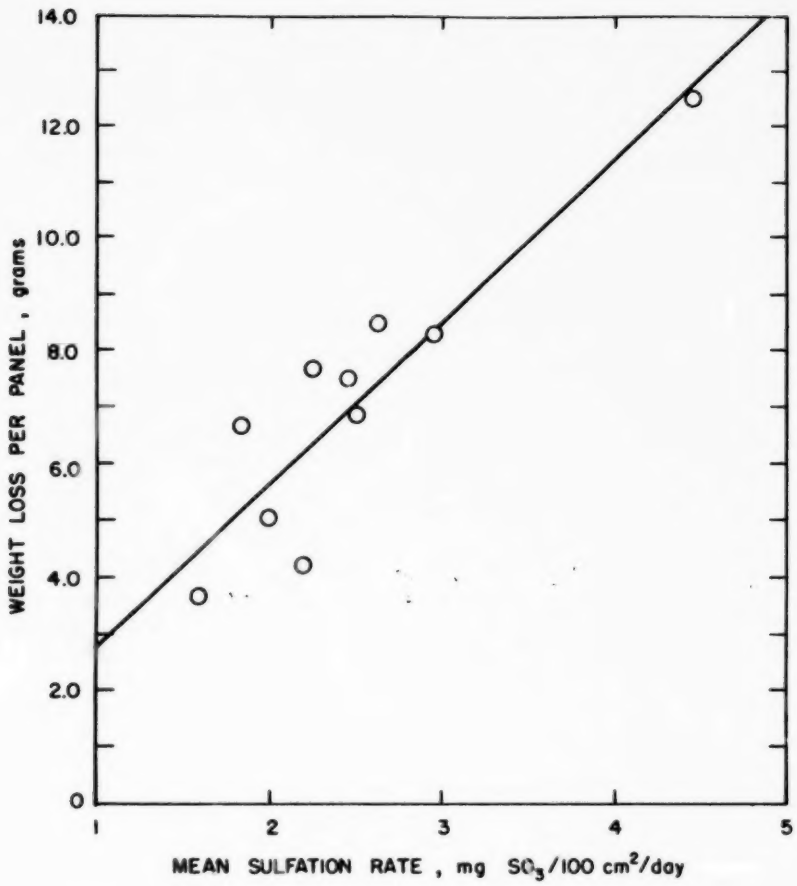

Figure 14. Relationship between corrosion of mild steel and corresponding monthly mean sulfation rate for a 3-month exposure at 10 metropolitan St. Louis sites (Dec. 1964 - Feb. 1965).

located at site coordinate* 472-680 (see map Figure 15). After 9 months, fine perforations had appeared in the panel at site 499-700, and had extensively covered the panel at site 472-680. The latter was estimated to have approximately five holes per square inch. The condition of three of the panels after 11 months is shown in Figure 18. During this exposure period, all the panels developed progressively dirtier surfaces; those in the East St. Louis and south St. Louis City areas became opaque. Panels in the Brentwood and Wood River areas remained essentially transparent and relatively clean.

Observations made after heavy rainfall during the fifth month of exposure indicated that the rain tended to clean the nylon quite well, although in some instances the panels remained dark gray and almost opaque. The texture of all exposed panels changed visibly, and the exposed fabric lost strength probably because of chemical

*Site coordinates refer to the cell to the north and east of the designated point.

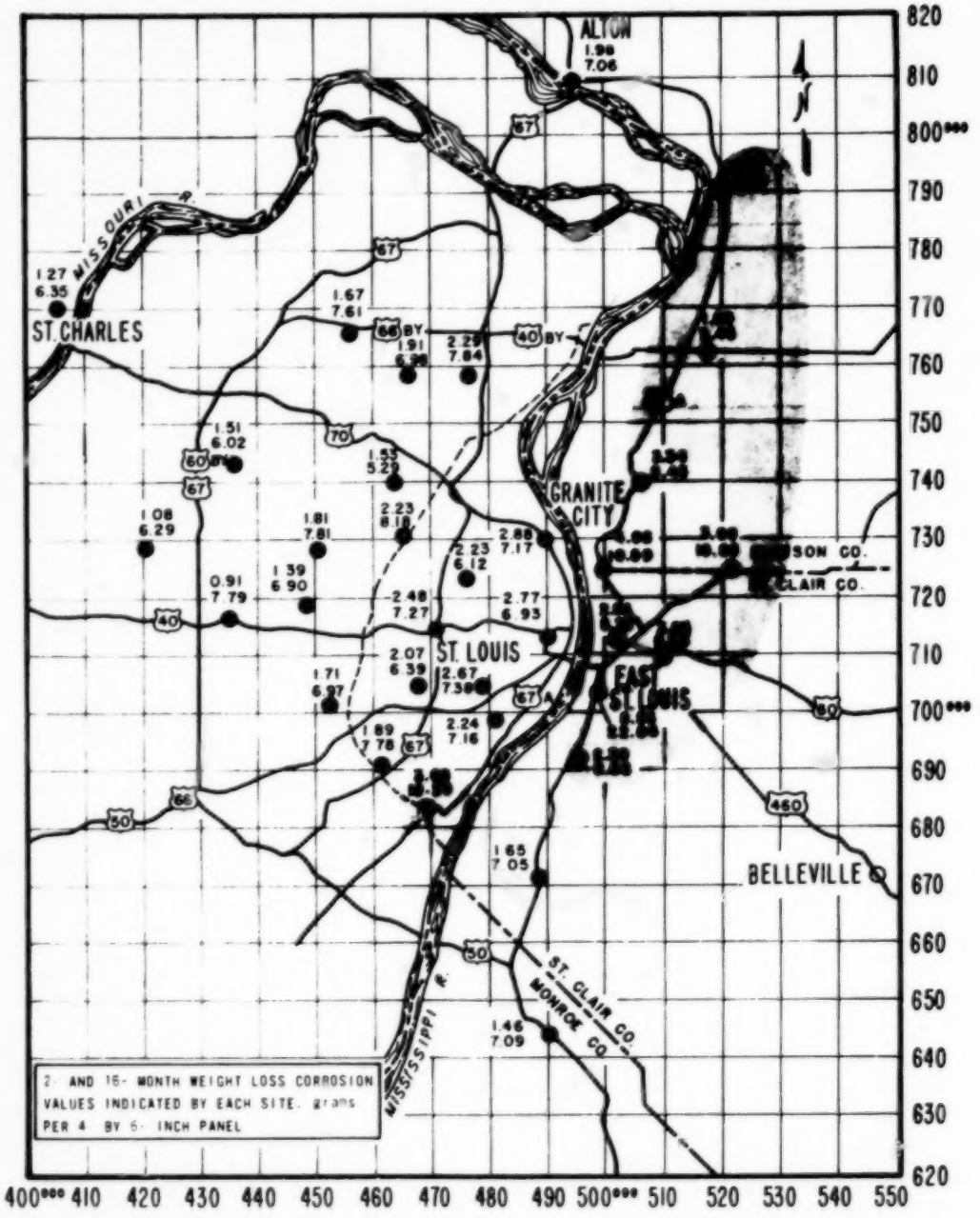

Figure 15. Corrosion exposure sites in St. Louis - East St. Louis area. Shaded portion of map indicates area having above-average corrosion of steel panels during 16-month exposure period.

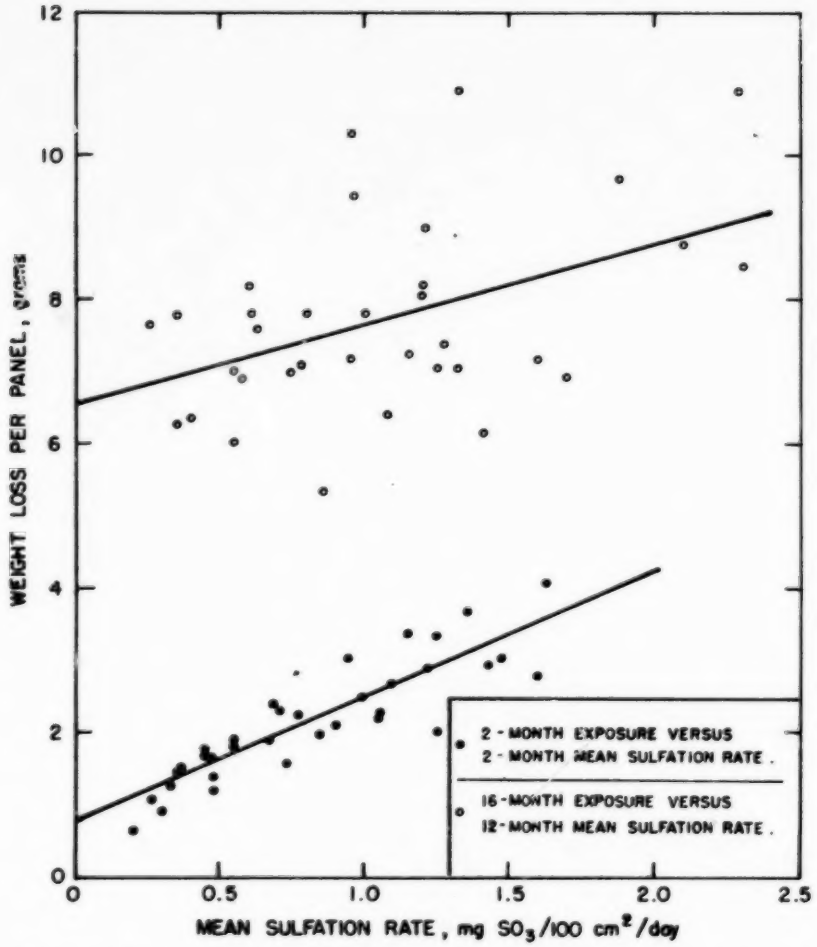

Figure 16. Relationship between corrosion of mild steel panels and corresponding mean sulfation rate measured at selected sites in St. Louis - East St. Louis Metropolitan Area from December 1964 through February 1965.

decomposition caused by ultraviolet radiation and air pollution. Unexposed fabric could not be torn by hand, but all exposed panels could be easily torn by hand. Panels exposed in areas of highest air pollution were found to be the weakest.

Nylon hose could have a similar response to that observed in these studies. The fabric used in the study was much stronger than material used for hose.

Effects on Exposed Cotton Fabrics

During the period June 1963 to June 1964, cotton fabrics were exposed at seven different sites in the Study area. The objectives of the study were to determine whether various levels of air pollution significantly damaged outdoor-exposed cotton

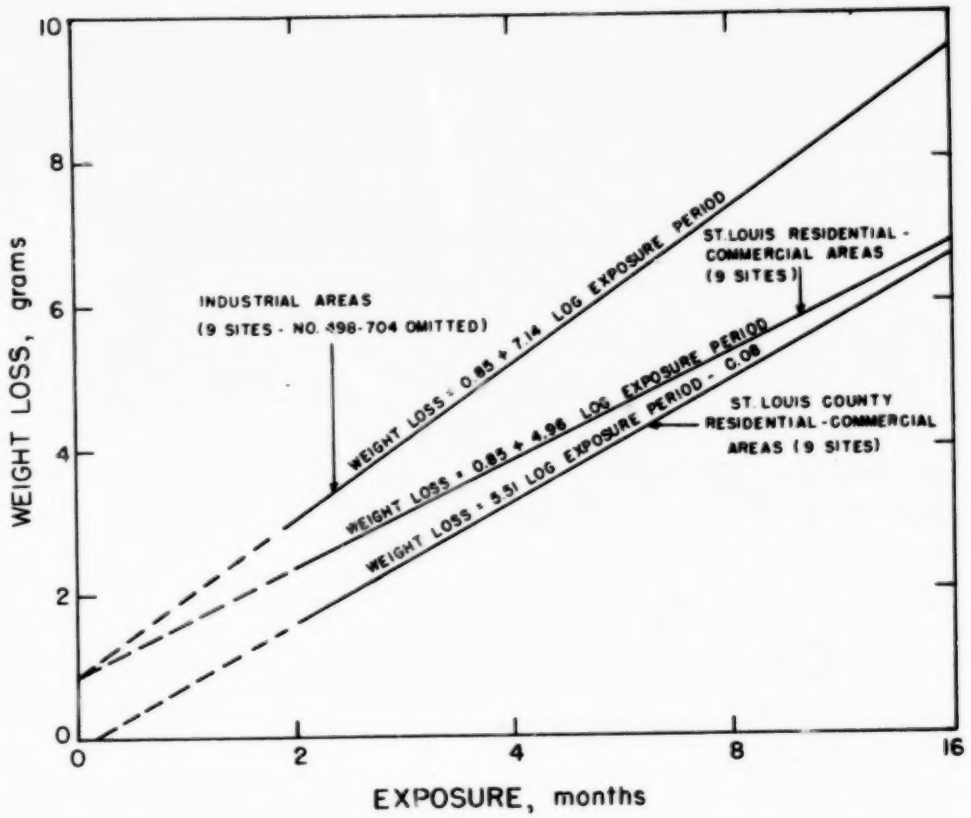
WEIGHT LOSS, grams
EXPOSURE, months
INDUSTRIAL AREAS
(9 SITES - NO. 698-704 OMITTED)
WEIGHT LOSS = 0.85 + 7.14 LOG EXPOSURE PERIOD
ST. LOUIS RESIDENTIAL - COMMERCIAL AREAS (9 SITES)
WEIGHT LOSS = 0.85 + 4.98 LOG EXPOSURE PERIOD
ST. LOUIS COUNTY RESIDENTIAL - COMMERCIAL AREAS (9 SITES)
WEIGHT LOSS = 3.51 LOG EXPOSURE PERIOD - 0.08
0
2
4
6
8
10
16

Figure 17. Mean corrosion rate of mild steel panels versus exposure periods for specified types of land use from April 1963 through July 1964.

fabrics beyond the damage normally caused by photolysis and biological effects. Two fabrics, a print cloth and an army duck cloth, were used. After exposure periods of 1 to 12 months, chemical and physical tests were made on samples of the cloths.

Figure 19 shows the loss in breaking strength with exposure time. Table 13 shows the sulfation, dustfall, and suspended particulates at the sites plotted in Figure 19. Figure 20 shows that there is a close relationship between breaking strength and fluidity (a chemical physical test of material degradation[102, 103]). (Fluidity is expressed in rhes, a unit equal to the reciprocal of 1 poise, which is a measure of viscosity.) Fabric test results were compared with the air pollution levels at the points where these fabrics were exposed. The rates of degradation of the cotton fabrics increased as air pollution levels increased for dustfall, suspended particulate, and sulfation.

Of these three, degradation was most directly related to sulfation levels. Visual examination, comparison of breaking strength values for exposed print cloth and duck samples, and the correlation of fluidity versus breaking strength (Figure 20) all indicated that degradation was not caused by biological factors, but by chemical action resulting from exposure to ultraviolet radiation and air pollution.

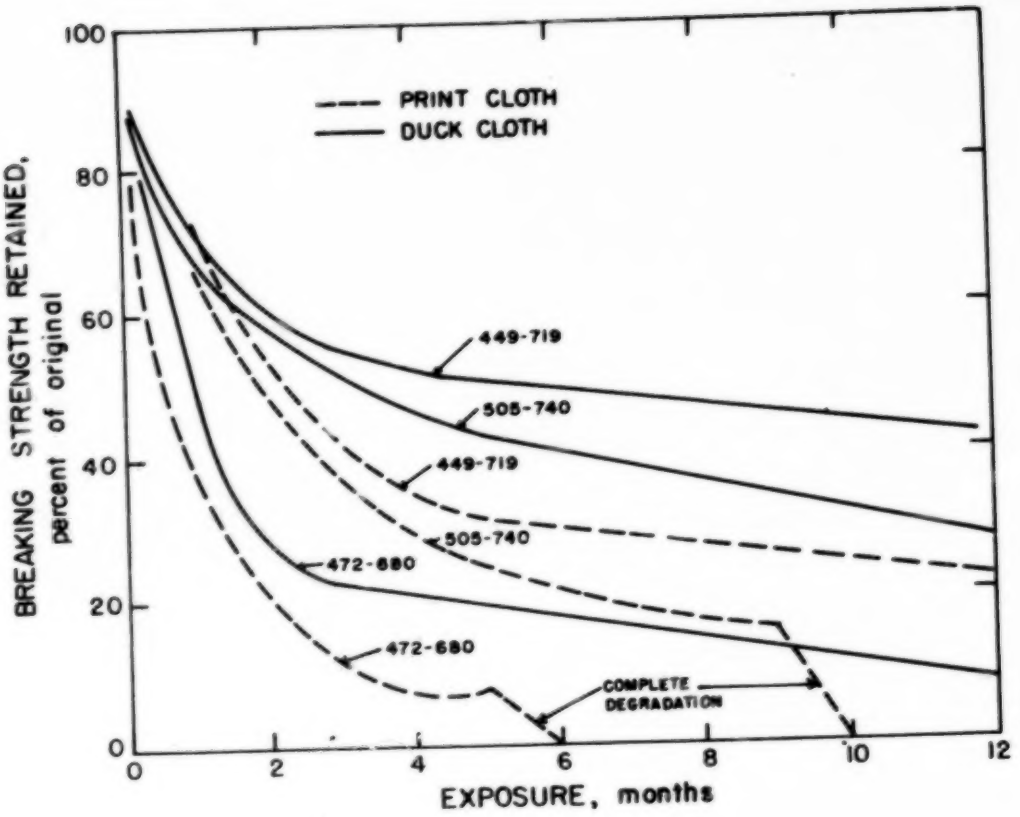

Figure 19. Percent of fabric breaking strength retained versus exposure time.

Table 13. MEAN POLLUTANT LEVELS

Site grid coordinates	Sulfation,[a] mg SO_3/ 100 cm^2/day	Dustfall,[a] tons/ mi^2/mo	Suspended particulate,[b] $\mu g/m^3$
449-719, residential, St. Louis County	0.56	14	84
505-740, industrial, Illinois	2.9	67	246
472-680, industrial, St. Louis	5.5	61	303

[a]Arithmetic mean, March 1963 through February 1964.
[b]Arithmetic mean, July 1963 through June 1964.

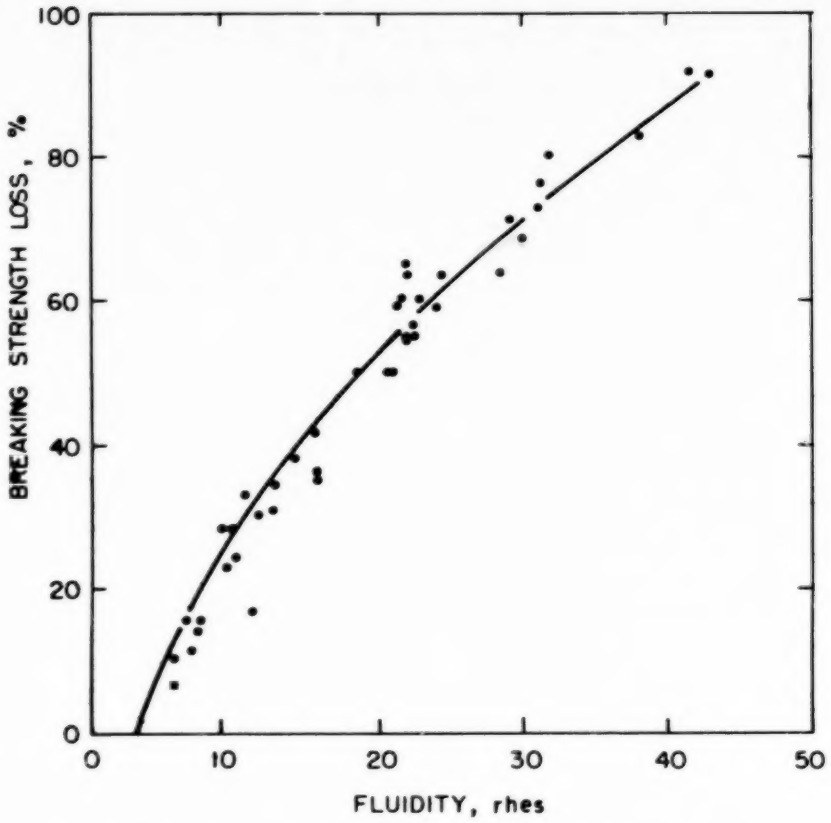

Figure 20. Loss in breaking strength as a function of fluidity for cotton duck cloth exposed from June 1963 to June 1964 (Results are plotted for all seven stations).

from the central business district as measured by the average time during rush hours hours required by an express bus to reach the central business district, (3) accessibility to highways as measured by the census tract touching a highway or a major thoroughfare, (4) shopping area accessibility as measured by a shopping area in the census tract, (5) industrial area accessibility as measured by the inclusion of an industrial area in the census tract, (6) school quality, (7) crime rates, and (8) state location - Illinois or Missouri.[104] Shopping area location, industrial area location, and crime rates proved to be unimportant in explaining variations in property values.

The remaining variables, however, explained practically all the variation in these property values. Air pollution as measured by sulfation was found to be significant in the overall explanation of property value variation; in fact, it was shown to be almost as important as highways and more important than state location, time from the central business district, or school quality. Partial regression coefficients calculated for sulfation indicated that if sulfation levels to which any single-family dwelling unit is exposed were to drop 0.25 milligram SO_3 per 100 square centimeters per day, the value of that property could be expected to

rise by at least $83, and possibly by as much as $245. If no offsetting market adjustments are assumed to occur, this conclusion can be generalized to include all houses in the St. Louis Metropolitan Area. If, therefore, sulfation levels were reduced by 0.25 milligram SO_3 per 100 square centimeters per day, but with no level below 0.49, the estimated property value increase in Dr. Ridker's sample area would range from $24 million to $72 million. If the sulfation levels were brought to a uniform 0.49 milligram per 100 square centimeters per day over the sample area, the estimated property value increase would range from $74 million to $219 million. If this analysis were applied to the entire St. Louis standard metropolitan statistical area, the increase in value at $83 to $245 per single dwelling unit per 0.25 milligram SO_3 per 100 square centimeters per day reduction would range from $28 million to $83 million. If a uniform sulfation level of 0.49 milligram SO_3 per 100 square centimeters per day were reached, the change in value would range from $85 million to $251 million. It seems doubtful that these increases in value could be obtained because the greater availability of pollution-free property would more than satisfy the demand. Although Dr. Ridker does not feel that his findings report every aspect of property value change, he does feel that they point to air pollution as an important contributing factor in depressing property values.

An analysis of an air pollution problem area adds further weight to these findings. In south St. Louis, Dr. Ridker selected an area in which an air pollution source caused a major complaint. This complaint, in 1962, in a quiet middle-class neighborhood, concerned offensive gases and fumes. It apparently was considered to be a serious problem because petitions against it were signed by 270 residents.

To assess the effect that air pollution had on property values in this neighborhood, apart from the changes in a general market condition, a study-control area as similar to the affected area as possible was selected. A comparison was made between recorded sales of property in the two areas for the years 1957 through July 1964. (See Figure 21). The control area, over this period, exhibited a slight upward trend in property values. During the period from 1957 to 1962 the property values in the south section of St. Louis remained stable; however, after 1962, when this area was subjected to increase air pollution, the polluted area showed a marked depression in property values. By taking the 1964 difference between actual property values and property values estimated by using control-area property indexes, an individual property value loss of $400 to $1000 each was estimated by Dr. Ridker. For the area under study, this amounts to a total property value loss of $306,000 to $765,000. The study is being continued (June 1966) to add sales data beyond July 1964; these estimates are, therefore, provisional.

Economic Effects of Open Burning

A report by the St. Louis County Health Department in January 1966[105] indicates the cost of open burning. The report results from a questionnaire survey of 52 fire departments. In 1965, 10,993 fire calls were received in the county. Of these, 1,203, or 11 percent, resulted from some type of open burning. Based on cost information from 20 percent of the fire departments, these fires cost the fire departments about $83,000 and the property owners $473,000, a total of $556,000 in 10 months of 1965. Regulation of open burning was reported to be effective in eliminating fire calls for this type of fire.

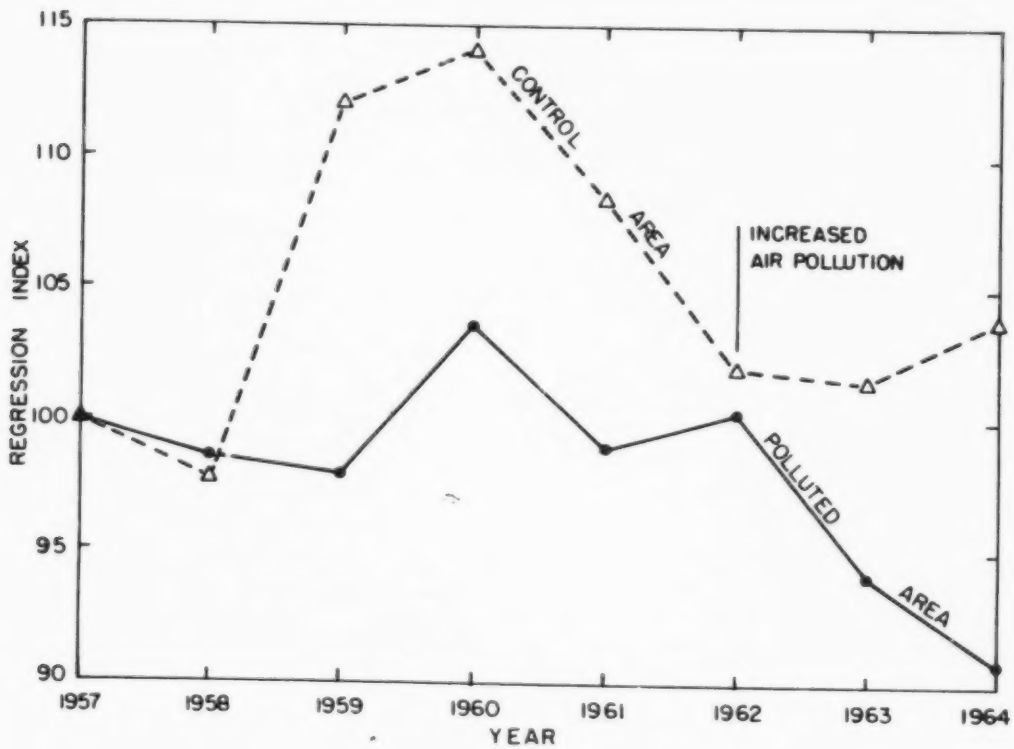

Figure 21. Comparison of property values in control area and area affected by offensive odors in 1962.

PUBLIC OPINION SURVEY - EFFECTS REPORTED

The effects of air pollution are not wholly measured by physical and biological means. The air quality, likewise, is only partly defined by physical measurements such as those reported in Volume III of this report. The opinion surveys reported in Volume VII reflect total air pollution effects as respondents sensed them. The surveys included responses to some air pollution effects not measured by physical and chemical means such as "bother," dirtiness, and odors and eye, nose, and throat irritation. They excluded some air pollution effects because they are not detected by the respondents' sense of smell, sight, or touch. Volume VII reports both the magnitude and distribution of effects in the air pollution basin. To a considerable extent the opinion survey results are used here to substantiate air quality goals selected on the basis of chemical, physical, and biological measurements.

The opinion survey revealed that 90 percent of the respondents were satisfied with air quality, 43 percent reported some bother with air pollution, and 35 percent

reported air pollution existing in their neighborhood when the respective pollutants were at the following levels:

1. Suspended particulates (high-volume sampler)
   - geometric mean, 78 to 85 $\mu g/m^3$
   - 99th percentile, 240 to 268 $\mu g/m^3$

2. Soiling index (AISI strip filter paper sampler)
   - geometric mean, 0.37 to 0.45 Coh/1,000 lineal ft
   - 99th percentile, 2.8 to 4.0 Cohs/1,000 lineal ft

3. Sulfation (lead peroxide candle method)
   - geometric mean, 0.42 to 0.73 mg $SO_3/100\ cm^2/day$
   - 99th percentile, 1.9 to 2.4 mg $SO_3/100\ cm^2/day$.

More people were found to be bothered by air pollution than recognized air pollution in their neighborhoods. This seems logical in a suburban way of life in which many people live away from highly polluted industrial and central city areas, but work in or travel through these high-pollution areas and, consequently, are bothered by the high pollution concentrations in such areas.

In general, there is agreement between goals selected by means of public opinion surveys and those based on physical, chemical, and biological measurements.

HEALTH EFFECTS - A SUMMARY STATEMENT

A summary statement comes from an address made in 1965 in Los Angeles by E. T. Blomquist, M.D., Assistant Chief, Public Health Service, Division of Air Pollution:

"The fact that air pollution in high concentration can cause widespread illness and death was amply demonstrated by tragic episodes in the Meuse Valley of Belgium, in London, and in Donora, Pennsylvania. These episodes were recognized and documented at the time they occurred but epidemiologic studies revealed that similar episodes could occur and, in fact, had occurred, without being noticed. For example, it was found, 9 years after the fact, that some 200 excess deaths occurred in New York City in 1953 during a period of air stagnation.

"In the long run, however, there is even greater significance in the health hazards associated with levels of air pollution to which millions of urban dwellers are exposed almost constantly. Knowledge of this aspect of the problem has been broadened and amplified through epidemiological and statistical as well as laboratory and chemical studies.' These investigations have covered a broad area ranging from correlations between urban air pollution and the incidence and mortality rates for various respiratory diseases to the effects produced by exposure of animals and, in some cases, human beings, to controlled amounts of specific air pollutants.

"The results of these studies can be summed up by saying that air pollution is associated with the occurrence and worsening of many serious respiratory diseases, including asthma, chronic bronchitis, lung cancer, and emphysema."

The foregoing remarks by Dr. Blomquist summarize health effects from an epidemiological point of view. The following quotation from the February 1966 Scientific American article "The Lung"[106] summarizes the same subject in this way:

"Other air pollutants - irritant gases, vapors, fumes, smokes, aerosols, or small particles - may give rise to a similar bronchial constriction. It is one of the ironies of man's urban way of life that exposure to the pollutants that produce severe and repeated bronchial constriction results in excessive secretion of mucus, a reduction in ciliary activity, obstruction of the fine air paths, and finally cell damage. These circumstances enable bacteria to penetrate to the alveoli and remain there long enough to initiate infectious lung disease. They are probably a factor in the development of such tracheobronchial diseases as chronic bronchitis and lung cancer. Thus man's advances in material culture increasingly threaten the air pump that helped to make his evolutionary success possible."

ECONOMIC EFFECTS - A SUMMARY STATEMENT

A 1958 estimate of economic losses due to air pollution in the United States was $65 per capita per year.[107] Applied to the Nation, this amounted to $11 billion for 1964, or $130 million per year for the Interstate Air Pollution Study area.

A number of economic effects were studied, observed, or reported in the Study area. Visibility was found to be reduced sufficiently by air pollution to affect airport operation and to obscure valuable views in certain parts of the Study area. Vegetation damage of several types was reported or found by observation and study. This damage was of the ozone or photochemical-smog-associated type, the sulfur dioxide type, as well as types of damage caused by other pollutants. Materials deterioration associated with air pollution was found by studies of steel corrosion, nylon fabric, and cotton fabric. Soiling effects occur and were measured by determining the soiling characteristics of the air. Property values were found to be decreased by $400 to $1,000 for each single residence in an air-pollution-problem area. Single-dwelling residences were found to have a potential increase in value of $83 to $245 each for each 0.25 mg SO_3 per 100 square centimeters per day decrease in sulfation.

The $130 million per year estimate of the cost of air pollution in the Study area is logical when the great variety of effects is considered. It would also seem that the air-pollution-related economic effects are basically matters of equity. This equity involves the importance of the purpose for which the air is being used by those who claim the air. This is illustrated by two photographs, Figures 22 and 23, taken in the central part of the Study area. Figure 22 shows the air being used for dilution of air pollutants from a number of sources located near each other. The second photograph, of the same area and air mass as the first, shows the St. Louis central city district as it is now being rebuilt. The new structures, changing the character of the area, represent an investment of at least $200 million. Possibly of more importance than the dollar amount of the change is the major change in functions and purpose of the entire metropolitan area illustrated by the central city district photograph. There is little doubt that the two photographs show the same air mass being used for conflicting purposes. The background of this conflict is amply stated by Bollens,[108] "Growing up in the age coal and steam, the older portions of St. Louis City reflect the high premium placed on land near transportation facilities. Until recently, the most important facili-

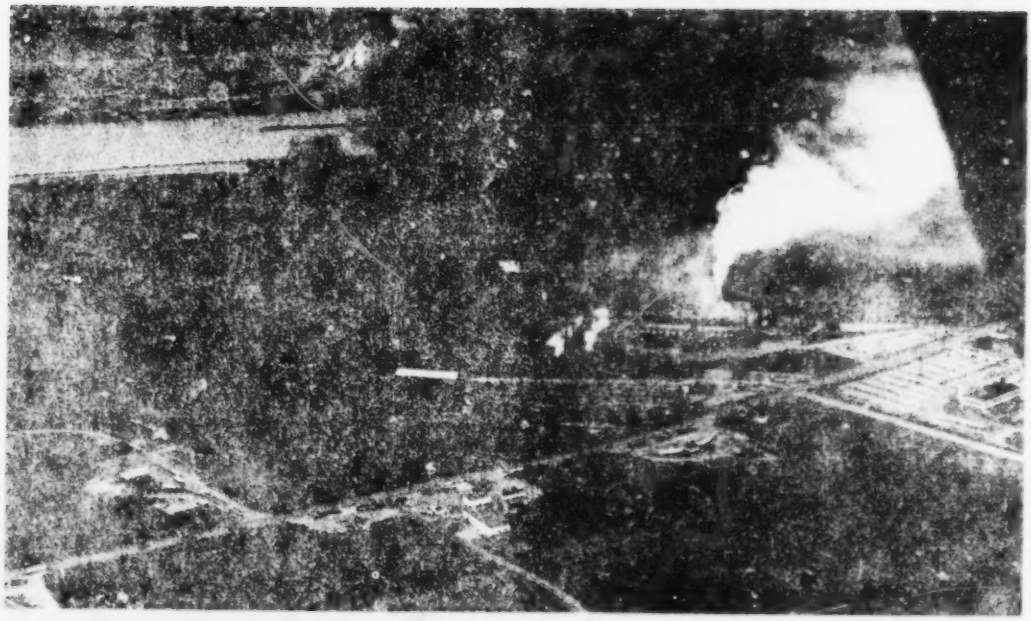

Figure 22. Air pollution in central city area.

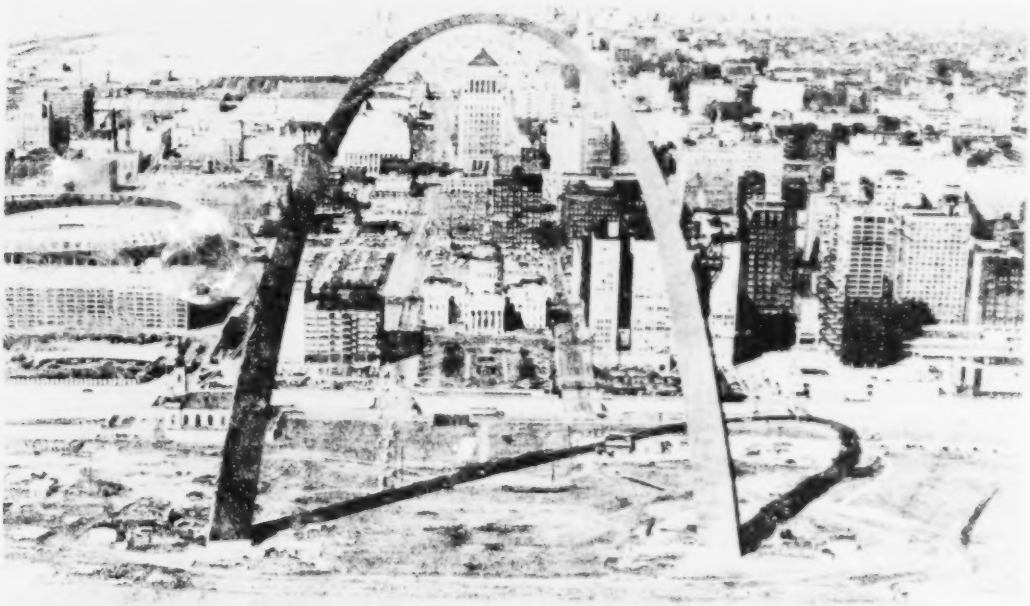

Figure 23. Urban renewal in central city area.

ties were the river and the railroads. Location of industry in such sections brought about the construction nearby of the extensive, crowded residential districts to house the labor force. Another heritage from the age of coal and steam is the thick film of grime covering many of the aged buildings in the downtown commercial center. This discoloration creates the impression that the older part of the City is even older than it is; only during the past two decades has the municipal government been able to suppress the use of fuels that once gave downtown St. Louis a dusky, evening aspect at noontime."

Future air use, including resolution of air-use conflicts typified by the two photographs, have not been decided for the Study area. To a considerable extent the Interstate Air Pollution Study has been dedicated to providing background information that will help others reach decisions concerning this important matter. In planning for the solution of air pollution problems having economic effects relating to potentially conflicting air uses, information and data will need to be obtained and analyzed on a continuing basis. These program activities must include urban planning as well as regulatory activities. The resulting bases for decision will need be acted upon through a suitable decision-making and program-implementation process covering the entire air pollution basin as a unit.

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